THE PHYSICAL AND

ECONOMIC FOUNDATION OF NATURAL RESOURCES

II

The Physical Basis of Water Supply and Its Principal Uses

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Foreword

THE PHYSICAL FOUNDATION of water supply is made up of many natural factors and among these there are various complex interrelations. Local and regional differences, especially in geology and topography and in the results of the interaction of the meteorological factors add to the difficulties of determining quantities of water and the manner of most effective use of available resources.

The economic foundation required for the appraisal of the relation of available water to human welfare is even less adequate than the physical base on which it necessarily rests. Economic analysis is handicapped especially because of inadequate quantitative data. For only a few areas are the quantities of water accurately determined. For many others only scattered measurements exist. In general it is the supplies yielded by undisturbed natural processes that are measured. It is not possible, since the techniques have not been perfected, to determine the quantities of water that could be made available when the needs for water require the employment of all feasible methods of water conservation. For some important features of uses of water there are no specific studies yet available.

Since appraisal of resources and evaluation of projects must proceed in the light of available facts there is special need for increasing the usefulness of scarce data and of securing qualitative judgment from scientists in the neglected segments of study.

The collection of articles on various phases of water resources in this publication brings together in more convenient form some materials otherwise available but scattered, and in other ways adds to the literature in the field. Some of the articles have been submitted by Federal agencies but several have been prepared by professors and engineers not in Federal service.

A general description of important facilities of water management, the ground water reservoirs of the United States, is appearing as number III in this series. Other features are being prepared for possible future publication.

Introduction

In my introduction to the preceding publication in this series, "Photosynthesis—Basic Features of the Process," there was an explanation of the extensive responsibility of the Committee on Interior and Insular Affairs in the field of natural resources. That document presented much valuable data and new discoveries on *photosynthesis*, the most important of all nature's contributions to the welfare of mankind. Members of the committee and others now have available the results of important new scientific discoveries which provide an explanation of some of the basic features of the process and therefore a more complete scientific foundation for an appraisal of many natural resource problems.

These studies have added greatly to the evidence of the importance of water as a resource by showing the need for an adequate and appropriate supply to obtain the most productive results in photosynthesis. Probably our greatest single weakness in natural resource management is our present deficiencies in scientific data about our water resources. On some phases considerable data have been accumulated but on others the data are but fragments of what is needed and some of the most important features have been most neglected.

The rapid increase in the size and scope of Federal projects in natural resources makes the formulation, at the earliest possible time, of an adequate scientific foundation program, the logical first step in a sound national resources program. Mistakes from projects formulated with inadequate information will often produce unfortunate results, in some cases the losses may be many times the cost of the scientific program that would be required for sound development.

The completion of the mapping and basic data programs and other segments of a more complete scientific program will require time. Even with the highest rate of acceleration that may be found feasible, adequate information will not be available for many projects that may be built.

The necessary professional manpower is only fractionally available and must be trained and attracted to the program. This will require dependable financing with assurance of program continuity. The necessary staff of scientists and technically trained personnel could not be assembled and their adherence to the program maintained without congressionally approved policies that will insure these results.

These deficiencies in the scientific foundation program in natural resources create difficulties for those responsible for formulating programs and policies for developing the resources of this great country, and lend great emphasis to the need for fostering preliminary or reconnaissance type surveys that will add as quickly as possible to our knowledge of the basic physical and economic features of our resources in order that we may plan our programs more wisely.

Great gains would come if the basic features of the unexplored resources could be established in a preliminary way and the meaning of all this for current projects made evident.

I have long been interested in this problem of more adequate basic data for our programs to develop our water resources. The human law maker should understand the natural laws with which he deals.

During the last dozen years I have passed from one authority to another the now famous, or "infamous," four questions. I still seek an answer but, as yet, a complete or adequate set of answers has not been available for any of the many areas in which as chairman of the committee I am interested. These are the four questions:

Let x represent any given geographical surface or area for which this information is sought.

First, what is the total annual average precipitation falling upon area x?

Second, of the total average annual precipitation what proportion gets into stream channels where it can be measured and utilized by man?

Third, of the total precipitation what proportion is returned to the atmosphere as vapor?

Fourth, of this precipitation what proportion gets into underground channels and reservoirs and what becomes of it?

I have propounded these questions on several occasions to Dr. J. R. Mahoney, senior specialist in natural resources, Legislative Reference Service of the Library of Congress. While he has not been able to provide the answers he has through cooperation with the scientists in the Federal agencies and others succeeded in formulating a program that was embodied in a bill to provide a comprehensive and adequate water resources basic data program, which I introduced into Congress as H. R. 6257 in the Eighty-first Congress, and reintroduced as H. R. 1637 in the Eighty-second Congress. Features of this bill and an explanation of the program may be found in part II of House Document 706 of the Eighty-first Congress, entitled "A Program to Strengthen the Scientific Foundation in Natural Resources."

These reports showed that some segments of the scientific program have been neglected relative to the amount of research concentrated in other fields.

Expecially lacking are:

1. Determinations of the rates, geographic distribution, and the gross volume of precipitation, the frequency in

which varying seasonal amounts of precipitation recur and the rates, variability, and amounts of potential evaporation and transpiration.

2. Knowledge of the magnitude and basic physical characteristics of the Nation's ground-water resources and of the facilities and techniques of subsurface-water management.

3. The necessary maps showing the physical features of the earth's surface as it relates to water management and the hydrologic characteristics of all surface and subsurface channels and facilities for storage and recharge of underground reservoirs.

4. Balance sheets of water-resource accounting showing for each catchment area and geographic unit the gross volumes of water from precipitation, the respective quantities of water consumed in various beneficial uses, the net gain or loss to surface or subsurface storage, the volume of outward drainage and the quantities dissipated in evapotranspiration.

5. The required data on the effects of variable supplies of water on plant growth and the potentials where water can be controlled and applied in close harmony with plant needs and the place of water management in a national program of photosynthesis.

6. The basic economic principles governing the allocation of water among its various uses, with appropriate evaluation of changing needs and reallocations.

7. The relative effectiveness of the different methods of water management, their respective costs, and the requirements for effective integration and coordination of the various uses.

8. The possibilities of recycling water for its most important nonconsumptive uses in areas where essential economic activities must be carried on with severely limited recurring annual supplies of water.

Following my suggestions and official request, as chairman of the committee, Dr. Mahoney has undertaken the task of bringing together reports of various scientists in order to provide a preliminary appraisal of some of these neglected features.

In pursuit of this program Dr. Mahoney has met a ready response from scientists in various Federal agencies and at various stages the assistance of scientists in universities and other non-Federal agencies has been sought. Some of these have been especially generous with their time and talents in preparing statements for the use of the committee without monetary compensation for their services.

The results of some of these studies are being printed for committee and other uses in a form similar to House Document 706. The second and third in the series are presented under the general title of "The Physical and Economic Foundation of Natural Resources" and the specific titles, II. "The Physical Basis of Water Supply and Its Principal Uses" and, III. "The Groundwater Regions of the United States, Their Storage Capacities."

JOHN R. MURDOCK, *Chairman*,
Committee on Interior and Insular Affairs,
House of Representatives.

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Economic Characteristics of Water

J. R. MAHONEY, *Senior Specialist in Natural Resources, Legislative Reference Service, Library of Congress*

WATER CONTRIBUTES, directly or indirectly, to the supplying of more human wants than does any other natural resource. It is an absolute necessity in the functioning of the human body, with regular daily supplies as important as food. It is essential to the maintenance of all plant and animal life. In varying degrees, water is vital in all segments of economic activity. As the population grows and the plane of living is raised, the total demand for water increases through new uses and through the intensification of old ones.

The most unique features of water supply are its cyclical replenishment in generally dependable recurring seasonal and annual patterns and its change of state from gas to liquid and back again in a continuous cycle. The supply of water is often deficient in relation to its numerous needs, and to the extent increasing needs cannot be offset by conservation measures this deficiency will become progressively more stringent.

In common with other scarce goods essential to human welfare, the value of water is the resultant of the relationship between two sets of factors—those governing its amounts and conditions of availability, and those determining the extent and nature of its uses. These constitute its supply and demand characteristics. Some features of both of these are unusual in their physical aspects and economic consequences.

The usual analysis of an economic good—one that is scarce in relation to the total volume of demand—begins with a portrayal of the conditions of supply, proceeds to the determination of the characteristics and volume of demand, and concludes with the appraisal of the impact of these opposing sets of forces and the resultant values.

Starting with the hydrologic and geologic factors governing the amounts of the water crop and the nature of its occurrence, the analysis must be extended to include the physical results of beneficial uses and their economic significance. There must be understanding of the physical conditions governing water supply and its availability, the technique of its effective management, the physical results from the use of water, and the values of its various uses.

Although important departures from the normal annual supplies are frequent, these fluctuations are generally around a central point from which excesses or deficiencies are reversed toward the normal. There are no discernable long-period upward or downward trends in annual supplies, but below or above normal precipitation may persist over a series of years, and the change is often to a succeeding period varying in the opposite direction.

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The amounts and distribution of precipitation over the earth's surface result from meteorological forces operating on a vast scale, but these have been insufficiently charted and measured. Great air-mass movements, following fairly definite recurring patterns of behavior, transport tremendous loads of moisture derived from regions of heavy evaporation, chiefly the oceans. A portion of this moisture is then released over the earth's surface through the operation of a different set of forces which provides broad regional patterns of precipitation. Uneven topography and other factors may produce marked local variations in its amounts and distribution.

For each restricted area it is necessary to accumulate measurements of precipitation and data on other meteorological factors, especially evapotranspiration (evaporation and transpiration) over a period of sufficient length to provide dependable interpretations of patterns of water supply. In general, water passes through a balanced cycle each year—precipitation equals evapotranspiration and runoff to the sea, except as modified by gains or losses to surface and underground storage.

The many and varied functions performed by water and the great extremes in its physical products and economic returns create complex problems in the formulation of programs for its most effective use. For their soundness these programs require the identification, measurement, and appraisal of all important physical and economic features of water supply.

The need for sound policies and an effective Nation-wide water resources program arises from its overwhelming importance for the country's welfare and the necessity of synchronizing all uses, including prospective future intensified uses. Appropriate Federal and State policies must necessarily be formulated and programs developed to accomplish these objectives. Far surpassing any other resource, and probably equaling the importance of all others combined, water has now become the center of immense conservation activity and rapidly mounting expenditures.

Major Uses of Water

Some of the most important uses of water are those which are nonconsumptive or nearly so—the generation of electric power, navigation, most industrial uses, and the great preponderance of supplies used for domestic purposes.

Runoff to the ocean may generally be classified as waste, although in the lower reaches of large rivers navigation is of economic significance to be provided for. In these lower river channels, however, there is much damage from floods and difficulties from unevenness in the rates of stream flow. Offsetting costs for protective facilities sometimes leave little or no net contribution to the country's welfare. It is generally prior to such accumulations in large open streams, that water finds its most vital uses.

Water used for direct human consumption and other domestic needs usually takes priority over all other uses where water supplies are scarce and some needs must be sacrificed. The total amount of water required for these purposes, however, is not large and, except for a fraction of the total, such uses are essentially nonconsumptive, although water quality may be impaired. There are often possibilities for treating and recycling of water where measures of conservation are needed to make the most of a limited supply.

Water is generally the limiting factor in the production of useful vegetation which supplies the requirements for all animal life. The primary (plants) and secondary (animal) products of photosynthesis[1] provide most of the necessities of life and furnish the raw materials for many other needs.

A national program for increasing the quantity and improving the quality of products vital to human welfare can be achieved more effectively through water management than by any other method. The undeveloped potentials are probably greater than for all others combined.

Characteristics of Water Supply

The amounts and distribution of the annual water crop is the resultant of meteorological and other forces operating well beyond man's control. These are, mainly, the vaporizing power of the sun drawing water into the atmosphere, the space relation of water and land surfaces, the geographical differential in the absorption of the sun's rays, air-mass circulation, and the topography of land surfaces.

In its vapor state, water is unmanageable and programs for its conservation are restricted to its liquid form on or under the earth's surface. The quantity available for management is a residual after many deductions from the original amounts precipitated. The manageable water crop is usually only a small fraction of total precipitation.

On reaching the land surfaces, the water supply is segregated into numerous independent segments by the topography of the earth's surface. For each basin or subbasin, the water crop is independent and the amount that can be brought under management will be determined by a set of geological and other factors peculiar to that catchment basin.

Water is seldom, if ever, distributed by these natural processes in amounts that completely harmonize with uses. The pattern of needs is generally markedly different from the pattern of supply as provided by nature. For its most vital uses, water is needed in a continuous unbroken supply, but with important daily and seasonal variations. This establishes the need for water control in order that irregular supplies may be collected and reallocated in harmony with use requirements.

[1] The process by which green plants fabricate numerous products out of water and carbon dioxide through the use of light energy from the sun and minor quantities of other elements.

Facilities of Water Management

The distribution of the facilities determining the amount of water that can be brought under management for its controlled uses are as variable as the geological conditions that have provided mineral deposits that are feasible of development. While it is possible with ground-water facilities as with coal or iron-ore deposits to mark out the general regions of their occurrence and after preliminary exploration to visualize something of their volume and qualities, it is difficult in either case to determine all the necessary factors for wise use without thorough mapping and adequate exploration and in many cases careful checking and observation after the facility is in operation.

Many areas throughout the United States are devoid of facilities for the production of minerals or the control of water supplies, while other areas have extensive deposits and facilities which remain unknown or can at this time be appraised only in a preliminary way. Difficulties with water supplies for many cities and industries that have reported trouble are in large measure merely concrete evidence of the lack of wisdom in choosing locations without first ascertaining the supply conditions of a resource that is essential to effective operation and in other cases mistakes in the use of a facility of water control which has only been partly studied and understood.

Variations in precipitation and even greater fluctuations in the volume of stream flow cause extreme variation in the amounts available for use. Unfortunately, the effectiveness of water in most of its uses is determined by the minimum rather than the average or maximum flow.

The minimum stream flow can be raised through storage reservoirs, and long-period regularization is possible where effective surface or subsurface storage facilities are available. The ultimate in efficiency can be achieved only where supplies, regardless of the irregularity of the pattern of their occurrence, can be placed in storage facilities from which withdrawals can be made in complete harmony with requirements for each use. Some uses, especially those of domestic consumption and energy generation, are best served by a regular and generally unvarying supply. These needs can usually be met, however, with less difficulty than can the widely varying requirements for efficient photosynthesis.

In response to the impact of a growing demand on an unexpandible water crop, techniques of water resources management can often be intensified to make a given amount of water serve more needs. Manageable water supplies can be enlarged to serve high-value controlled uses through reduction of wasteful evapotranspiration, suppression of

low-value uses, and by increasing the efficiency of facilities of control.

Tremendous amounts of water now wasted into the atmosphere through evaporation from open water surfaces, wet ground, and through transpiration by useless vegetation, provide potential supplies that can be salvaged for transfer to high-order uses where appropriate water management facilities are available. Low-order economic uses also account for a large portion of the total water crop. For each area the water-control facilities will limit the proportion of the total water crop that can be made to serve high-order consumptive uses.

Techniques are being developed which provide for important nonconsumptive uses of water through treatment and reuse in closed systems requiring only minor replenishments. This would generally necessitate effective underground water resource management since surface storage is usually subject to large losses from evaporation and seepage. Such losses would not be tenable in a recycling system requiring purification and/or distillation.

Subsurface reservoirs with impervious enclosures and their stored water shielded from the vaporizing forces of the atmosphere would permit an accumulation of reserves, even in desert areas, sufficient to meet substantial domestic and industrial needs. Water could thus be provided in places where the annual recurring water crop is only a small fraction of the total volume of water used.

Use of Water in Photosynthesis

Water is used jointly with several other important resources in the process of photosynthesis. Significantly, all these other resources—the light energy from the sun, carbon supply from the atmosphere, and the numerous mineral elements from the soil—can be used effectively only where there is an adequate supply of water. Because of the limited amounts and the precarious and uncertain supply of water, these other valuable resources frequently go to waste from nonuse, or yield only a fraction of their potential.

These combined vital functions supplied by water in the process of photosynthesis, coupled with the fact that it is the factor most subject to control, makes water management the dominant means of controlling and improving the process.

The relation between the quantity of water and the productive results of photosynthesis is much less direct than the relation between the pattern of its availability and the pattern of the energy supply—light from the sun. There is for each successive change in light intensity and other characteristics of the energy supply an appropriate amount of water for maximum results. Either too much or too little reduces the harvestable product, often drastically.

It is the possibility of providing this balanced water supply that is the dominant factor in appraising the facilities of water control for irrigation and especially for supplementary irrigation. A limited quantity of water under control applied in exact harmony with the requirements for maximum photosynthesis may produce a larger physical product than large amounts applied in the manner that is typical of most irrigation.

Large oversupplies often impair the total products as much as water deficits. Water requirements of plants are determined primarily by meteorological forces which not only vary with the seasons but also have a distinct daily pattern following closely the variable intensity of the sun's light. No area in the entire country provides water at the times and in the amounts that conform exactly to these patterns and seldom is maximum photosynthesis achieved. Water deficits for plants may occur even when large annual surpluses are precipitated. Heavy storms may be only fractionally usable by growing plants and light storms are often of small consequence.

Evaporation From the Sea as a Source of Moisture for Rainfall in the United States

RICHARD H. FLEMING, *Chief, Division of Oceanography, United States Navy Hydrographic Office*

FROM EXPOSED water and land surfaces moisture continually evaporates into the air where it exists in vapor form. This vapor is transported in accordance with the atmospheric circulation and is finally condensed into fog or clouds, from which a part is precipitated as rain or snow. After precipitation a large proportion returns to the original source, the ocean, thus completing the *water* or *hydrologic cycle* of transformation and transportation.

Until several decades ago a theory of a land-derived source of precipitation was advocated by hydrologists and climatologists. It was believed that the greater part of the moisture precipitated over the continents was water which had previously been acquired by the atmosphere by the processes of land evaporation and transpiration. This view of the hydrologic cycle minimized the flux of water in the atmosphere from the oceans and essentially equated such flow to the water lost by the continents as surface runoff and subsurface seepage. The theory of land-derived precipitation was first attacked by Holzman (8) in 1937. His study, based on newly available upper-air wind and humidity data, advanced the hypothesis that essentially all precipitation is derived from oceanic water vapor. He maintained that precipitation is derived from maritime air masses; that evapotranspiration occurs into continental air masses; and that, since the air masses are distinct, there can therefore be no important physical connection between the processes of evapotranspiration and precipitation. While Holzman was unable to advance conclusive proof of these statements, the theory of an oceanic source for precipitation has been widely accepted by hydrometeorologists.

The oceans are of vast importance in the water cycle because they serve as sources of heat and moisture for modifying cold and dry air masses. Because of the prevailing west-to-east air movement in our latitudes, the Pacific Ocean is a great source region for air with maritime polar characteristics. Continental air masses, originating in Asia and Alaska, move over the Pacific and absorb heat and moisture from the water. Convection, as a result of heating from below, brings about a transport of water vapor and heat upward, producing a fairly steep lapse rate and near-saturation humidities up to rather high levels. The resulting maritime polar-air mass is the principal one associated with precipitation on the Pacific coast. Likewise, the Gulf of Mexico, the Caribbean Sea, and the Pacific Ocean south of the tip of Lower California are important source regions for maritime tropical air which invades the United States from the south. As the name implies, this air is very warm and humid and when it is forced upward by topography, by surface heating over land, or when it overruns colder air in the vicinity of fronts, its moisture condenses and falls as precipitation. Of lesser importance is maritime polar air of Atlantic origin. This air, which is usually neither as moist nor as warm as maritime polar air of Pacific origin, occasionally affects the weather of the Atlantic coast of the United States.

The role of the oceans of the earth in the water cycle is further emphasized by the following figures from Wüst (20):

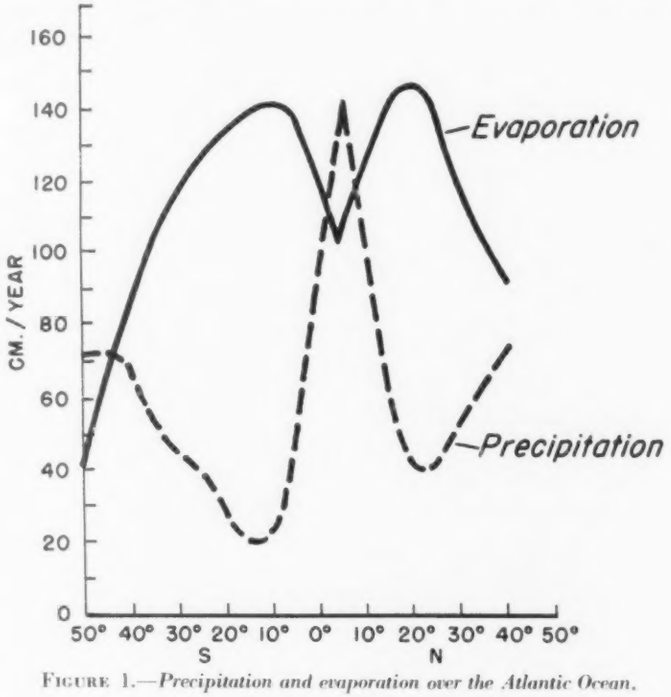

FIGURE 1.—*Precipitation and evaporation over the Atlantic Ocean.*

	Acre-feet	*Cubic kilometers per year*
Total evaporation from the oceans	275, 000, 000, 000	334, 000
Total precipitation on the oceans	244, 000, 000, 000	297, 000
Water supplied to the oceans by runoff	31, 000, 000, 000	37, 000
Total precipitation on land	82, 000, 000, 000	99, 000
Evaporation from land surfaces and from inland seas	51, 000, 000, 000	62, 000

For purposes of comparison, it may be mentioned that the capacity of Lake Mead, above Boulder Dam, is 45 cubic kilometers.

The function of the oceans in supplying moisture to the atmosphere through the process of evaporation will be discussed here. Methods for determining the rates and total amounts of water evaporated from the oceans will be described, and charts and tables showing the quantitative results obtained by leading investigators in the field will be presented.

Evaporation is a net flow of molecules from liquid to vapor. When the flow is in the other direction, *condensation* is occurring. Although it is complementary to precipitation and of equal importance, there is much less quantitative information about the rate of evaporation. This is due to the fact that, while the measurement of precipitation is direct and readily made, evaporation must be determined indirectly from suitably-made observations. The computation of exactly how much substance will evaporate under known conditions is difficult enough in the laboratory. In nature, where there is no control of causative factors and where it is difficult to measure the prevailing conditions accurately, the computation is approximate at best. A few qualitative statements can be made, however:

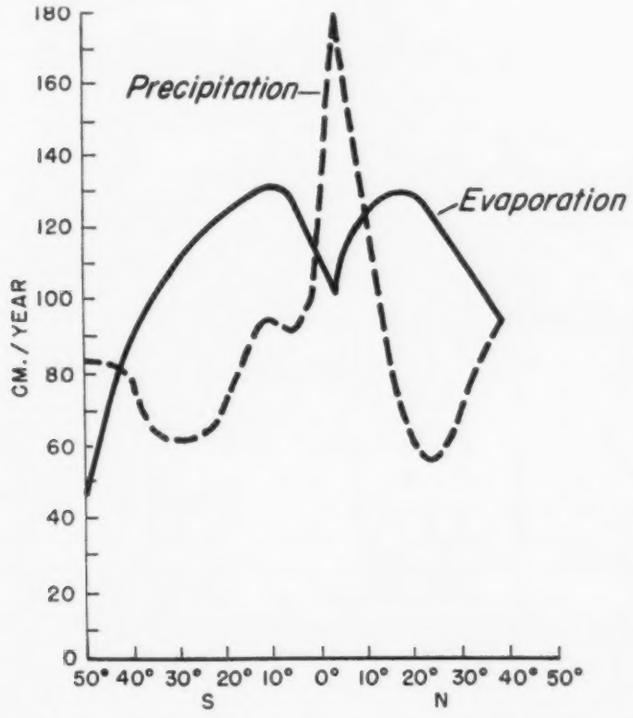

FIGURE 2.—*Precipitation and evaporation over the Pacific Ocean.*

1. Evaporation is proportional to the difference between the saturation vapor pressure at the temperature of the water and the actual vapor pressure of the air. It must therefore be expected that the greatest evaporation occurs when cold dry air flows over warm water. Under these conditions upward diffusion of water vapor will be facilitated because the turbulence of the air will be fully developed owing to unstable stratification in the very lowest layers.

2. Evaporation will be continuous only if energy is continuously received from some outside source (e. g., insolation).

3. Evaporation will be proportional to the rate at which vapor is carried away from the immediate vicinity. The evaporation rate in still air, for example, is much smaller than evaporation into a wind.

Methods for determining evaporation from the oceans

Our present knowledge of evaporation from the oceans is derived partly from *pan observations* and partly from computations based on consideration of the energy budget and the *mass transfer by turbulent processes* of water vapor from the ocean to the amosphere. The *water-budget* method, whereby evaporation is determined by measuring inflow, outflow, and changes in storage, obviously cannot be applied to the oceans.

Observations made from pans on shipboard were first used to gain an insight into the rate of evaporation from the sea. Such observations give values of evaporation which are too high partly because the wind speed is greater at the level of the pan than at the sea surface and partly because the difference in vapor pressure in the air and that of the evaporating surface is greater at the pan than at the sea surface. Wüst (20) has analyzed the decrease in wind velocity and the increase in vapor pressure between the average level of the pans used on shipboard and a level of a few centimeters above the sea surface and arrived at the conclusion that the measured evaporation rates must be multiplied by 0.53 in order to represent the evaporation from the sea surface.

Pan observations have also been used to determine evaporation from lakes and reservoirs where the pans could be located at the same level as that of the surface of the body of water. Considerable work has been done by investigators relating evaporation from a pan of a certain type and evaporation from a body of water. This method, too, has been criticized because the "pan coefficients" determined experimentally for various pans apply only for the conditions under which they were determined.

Computing evaporation on the basis of the energy budget is based on the fact that over the oceans as a whole the heat loss over the sea surface during the course of a year must, for all practical purposes, equal the total incoming radiation absorbed at the surface. For small areas of the sea surface, the evaporation rate in grams per square centimeter of surface, or simply the centimeters of water evaporated, may be determined entirely from energy rendered available for that purpose in accordance with the equation:

Equation 1 $$E=\frac{Q_t-rQ_t-Q_b-Q_c-Q_v}{L_t}$$

where Q_t = total heat radiated from the sun, sky, and clouds reaching the sea surface (depends primarily on the sun's altitude, cloudiness of the sky and absorption by the atmosphere).
r = fraction of incoming energy reflected (depends on the elevation of the sun and roughness of the sea surface).
Q_b = heat lost through back radiation from the sea surface (depends mainly on the temperature of the sea surface and water content of the atmosphere).
Q_c = sensible heat exchanged between the sea and atmosphere by conduction and convection.
Q_v = heat added or removed from the unit water column by advective processes.
L_t = latent heat of vaporization at water temperature t.

In equation 1, Q_t, Q_b, Q_c and Q_v are expressed in gram calories per square centimeter. When using the equation to compute evaporation, Q_v must be neglected since it cannot be evaluated. Methods for the practical determination of Q_t, r and Q_b have been devised by various investigators, viz., Mosby (15), Kimball (11), Ångstrom (2), Schmidt (16) and Asklöff (3). Knowing the values of these terms, it is possible to determine a quantity, Q_a, which is the amount of heat available in the sea to be used in part for evaporation, i. e., Q_e or EL_t, and the remainder for heating the atmosphere, Q_c. Thus

Equation 2 $$Q_a=Q_c+Q_e$$

To obtain the amount of heat available for evaporation, it is only necessary to determine the portion of Q_a which is released to the atmosphere as sensible heat. Early investigators assumed a constant value of 0.1 for the ratio, Q_c/Q_e, although it has long been known that the ratio is highly variable both with respect to seasonal and regional distribution. Bowen (5) has derived an expression for the ratio of heat losses by conduction and by evaporation, and his formula was later affirmed by Sverdrup. The formula for the ratio, often referred to as the "Bowen ratio" and indicated by R, is

Equation 3 $$R=\frac{Q_c}{Q_e}=0.50\left(\frac{t_w-t_a}{e_w-e_a}\right)\frac{P}{760}$$

where t_w and t_a = temperature in degrees centigrade of water and air respectively.
e_w and e_a = vapor pressure in millimeters of water surface and air.
P = atmospheric pressure in millimeters.

Combining equations 1 and 3, it is possible to arrive at the following formula which lends itself readily to making computations of evaporation over the oceans using available data:

Equation 4 $$E=\left[\frac{Q_a}{1+0.50\,\dfrac{t_w-t_a}{e_w-e_a}}\right]\frac{1}{L_t}$$

Sverdrup (17) has suggested a second method for computing evaporation as a function of moisture distribution and wind movement within the turbulent layer of the atmosphere. The basic assumption behind this method is that there is a transport of water vapor from the sea surface to the atmosphere by ordinary diffusion through a shallow boundary layer and by eddy diffusion through the turbulent layer above. Sverdrup's formula, which is not well suited for numerical computation, has been simplified by Jacobs (9) to give the 24-hour evaporation in millimeters:

Equation 5 $$E=0.108\ (e_w-e_a)\ W_a$$

where e_w and e_a = vapor pressure in millibars at the sea surface and at a height of 6 meters.
W_a = wind speed in meters per second at 6 meters.

Equation 5 applies only to an adiabatic atmosphere and gives values for E which are somewhat too great under stable atmospheric conditions. However, when computing evaporation over a period of days or longer, no serious error is introduced as the amounts computed under stable conditions are small when compared with those computed under adiabatic conditions.

Evaporation Rates Over the North Atlantic and North Pacific Oceans

Until the last decade only the *mean annual* evaporation over the oceans had been computed. Recently a more comprehensive investigation of the *seasonal* and *intralatitudinal* variations of evaporation has been completed by Jacobs (10) and the results of his work will be described at some length here. Jacobs approaches the problem on the basis of both energy and turbulence considerations using equations 4 and 5 to compute the mean annual evaporation for four selected areas in the North Pacific and North Atlantic Oceans where the latitudinal transport of water (north and south currents) is at a minimum. In making the computations, recently published climatic data on humidities, sea-surface temperatures and wind speeds were used. The two methods of computation have then been compared; (1) to determine the amount of statistical adjustment necessary to be applied to the observational data and, (2) to determine the validity of the turbulence method for computing evaporation. Table 1 shows the results of the two methods of computation:

TABLE 1.—*Mean annual evaporation (E') for selected areas computed by means of the energy equation (equation 4) compared with mean annual evaporation (E'') computed by the turbulence equation (equation 5)*

Ocean	Latitude	Longitude	E′	E″	E′/E″
North Atlantic	40–45N	20–50W	[1] 84.0	[1] 88.3	0.95
Do	20–25N	25–65W	167.5	94.2	1.78
North Pacific	40–45N	140W–160E	67.7	55.8	1.21
Do	20–25N	130W–140E	148.2	113.2	1.31
Average			116.8	87.9	1.32

[1] Centimeters per year.

Except in one case, the values derived from equation 5 are lower than those computed from equation 4. The mean annual evaporation for the four areas is 87.9 centimeters per year when computed from turbulence considerations and

116.8 centimeters per year when computed on an energy available basis. Jacobs attributes this difference to inaccuracies in humidity observations. Assuming the differences as being consistent, he prepares a correction factor (average of $E'/E''=1.32$) which he applies to equation 5, obtaining:

Equation 6 $$E=0.143\ (e_w-e_a)\ W_a$$

Using equation 6 and available climatic data over the oceans, Jacobs (10) has computed mean daily evaporation rates within each 5-degree square over the North Atlantic and North Pacific Oceans during winter (December, January, February) and during summer (June, July, August). Once the values of evaporation had been obtained, Jacobs used the Bowen formula (equation 3) to obtain a similar distribution of values of sensible heat given off from the oceans to the atmosphere. Charts showing the distribution of evaporation rates and sensible heat loss from the oceans are of interest to the meteorologist, who is concerned with the amount of latent energy in the form of water vapor which is rendered available for meteorological processes and with

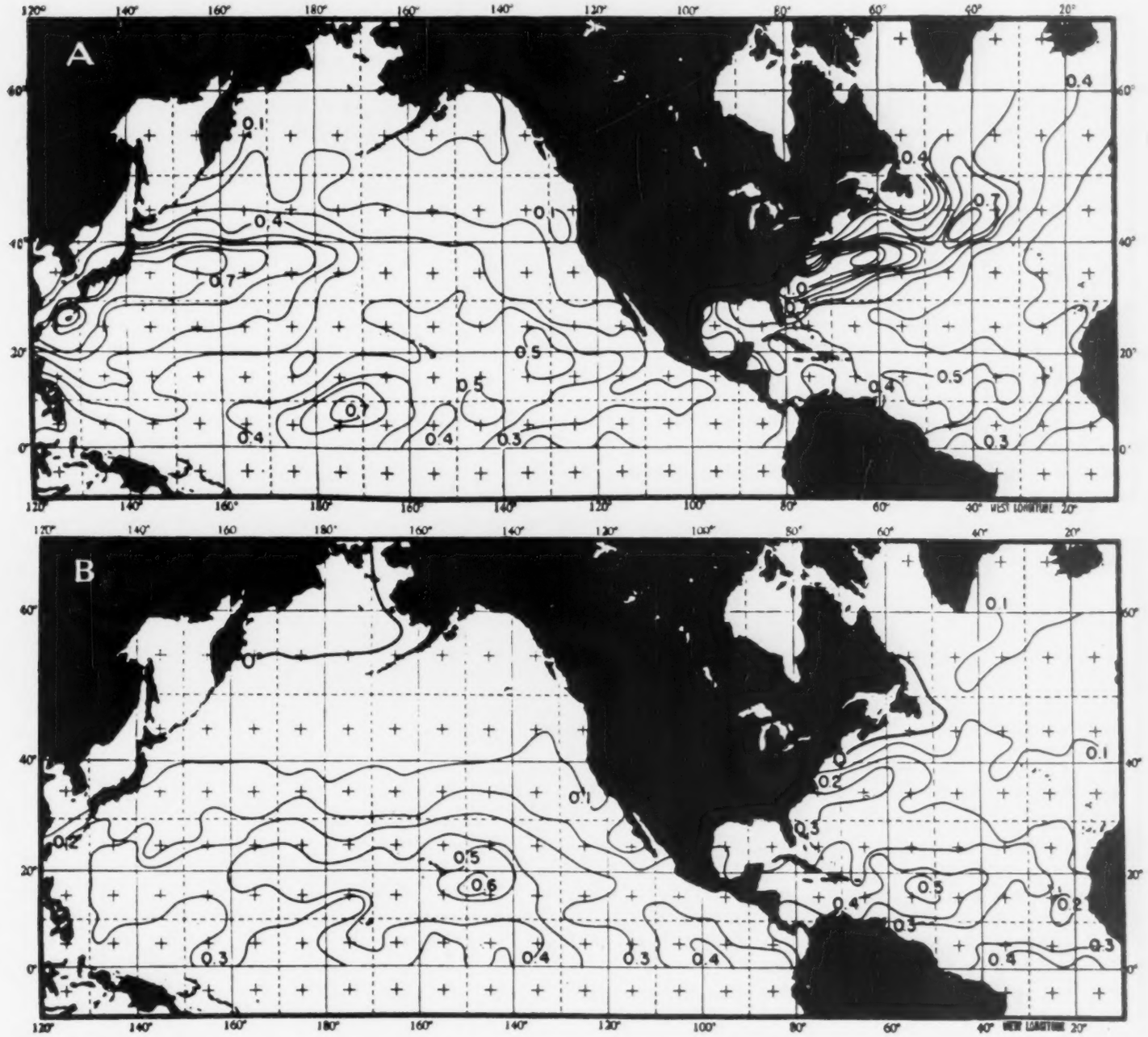

FIGURE 3.—*A. Distribution of mean daily evaporation rates (in grams of water per square centimeter of surface or in centimeters of water) over the North Atlantic and North Pacific Oceans during winter (December, January, February).*

B. Distribution of mean daily evaporation rates over the North Atlantic and North Pacific Oceans during summer (June, July, August).

the amount of heat added to or subtracted from the lower layers of the atmosphere. All water areas of importance as source areas or as modifying regions for air masses of the United States are included in Jacobs' investigations.

Reference to figures 3, 4, and 5 shows the following facts concerning the evaporation rates over the North Atlantic and North Pacific Oceans:

1. Evaporation over the oceans is nearly everywhere greatest in winter, least in summer and greater in autumn than in spring. The only major exceptions are near the Equator in the eastern parts of both oceans where the maximum occurs in summer, and in the south-central tropical North Pacific where there is a slight maximum in spring (fig. 3).

2. The regions of greatest evaporation are those of northerly flowing ocean currents; i. e., along the western sides of the oceans within the Kuroshio and the Gulf Stream. Secondary areas of high evaporation occur within the tropical trade-wind belts of both oceans where a high evaporation rate is associated with dry descending air currents in these regions. The regions of least evaporation are those of southerly flowing ocean currents along the extreme northwest coasts and along the eastern sides of the oceans. Low evaporation rates are also found in the eastern equatorial belts of both oceans where a low evaporation is associated with the northerly flowing cold currents from the Southern Hemisphere which cross the Equator in these regions. In winter, evaporation reaches values as high as 1.14 centimeters a day in the Gulf Stream and 0.94 centimeters a day in the Kuroshio. In midlatitudes along the eastern sides of the North Pacific, the winter evaporation is of the order of 0.15 centimeters a day and in the eastern North Atlantic 0.25 centimeters a day.

3. The zones of maximum annual evaporation in the North Atlantic occur farther north than in the North Pacific; viz, within the latitude range 35° N. to 40° N. in the Atlantic and within the latitude range to 25° N. to 30° N. in the Pacific Ocean (fig. 4).

4. The seasonal variations of evaporation are greatest in midlatitudes and along the western sides of the oceans and somewhat greater in the North Atlantic than in the North Pacific.

5. Evaporation is a positive quantity for all oceans except during summer for several small areas at high latitudes in the northwest portions where condensation of water vapor on the sea surface occurs.

It should be mentioned that the mean seasonal data shown in figures 3 and 4 are by no means representative of instantaneous conditions over the oceans. Nonperiodic variations in the rates of evaporation over the oceans do occur and the areas of maximum and minimum evaporation also vary in both intensity and position. For example, over the Kuroshio and the Gulf Stream, at times of outbreaks of cold, dry air in winter, the evaporation values may occasionally be extremely high. On the other hand, when polar fronts are located near the east coasts and the air masses over the sea are of southerly origin (i. e., moist and warm), the evaporation in these areas must reach low values.

The Total Evaporation Over the North Pacific and North Atlantic Oceans

The total volume of water evaporated from the Atlantic and Pacific Oceans between the Equator and 60° N. is shown in figure 5. These values are quite different from those in figure 4 representing the evaporation per unit area surface because of the unequal distribution of areas of sea surface at

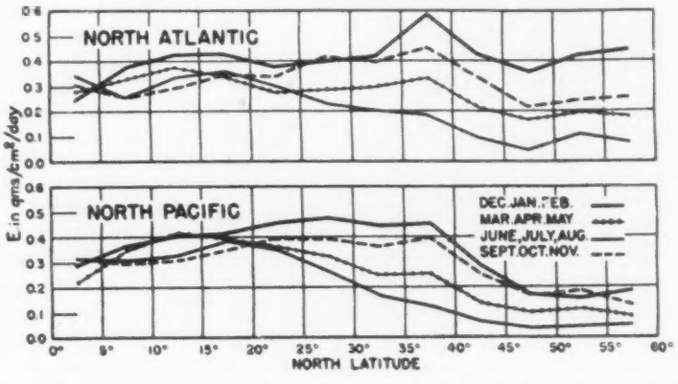

FIGURE 4.—*Seasonal values of evaporation for various latitudes in the North Atlantic and North Pacific Oceans.*

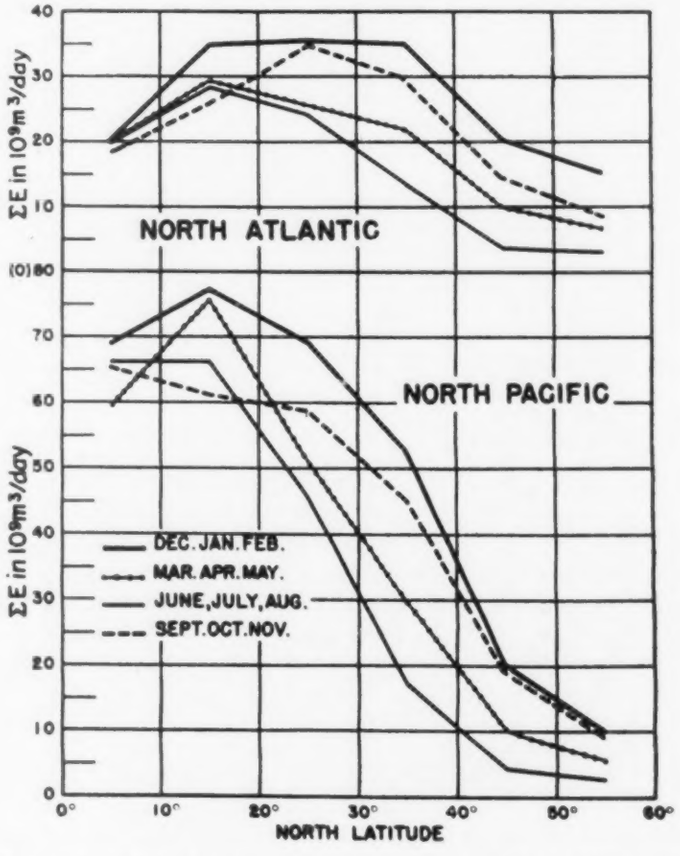

FIGURE 5.—*Total volume of water evaporated over the North Atlantic and North Pacific for various latitudes and seasons.*

various latitudes over the Northern Hemisphere. The curves show that the greatest quantity of water is evaporated in the lower latitudes during all seasons and that the quantity is greatest in winter, least in summer, and somewhat greater during autumn than in spring.

Although the area of the North Pacific between the Equator and latitude 60° N. is 67.1 percent of the total area of both oceans between the same parallels, it accounts for only 66.5 percent of the total water evaporated from both areas, because of the slightly greater rate of evaporation in the North Atlantic. The total volume of water evaporated from the North Pacific during the course of the year averages 90,232.4 cubic kilometers, which is equivalent to an evaporation rate of 111.4 centimeters per year. The total volume of water evaporated from the North Atlantic during the year amounts to 45,490 cubic kilometers per year, equivalent to a mean depth of 114.8 centimeters of water evaporated annually. The quantity for both oceans is 135,722.4 cubic kilometers, which is equal to a rate of 112.5 centimeters per year. The higher evaporation rate in the Atlantic appears to be caused by a smaller amount of heat given off to the atmosphere. There is also some evidence that cloudiness is greater over the North Pacific than over the North Atlantic. If this is true, it means that the North Atlantic has a slight excess of energy at the surface available for evaporation.

As mentioned previously, Wüst (20) has derived values for the mean annual evaporation rates at various latitudes in the oceans by reducing shipboard pan observations. His figures, which are for 5-degree parallels in the North Atlantic and North Pacific, extend only from the Equator to 40° N., however. By taking the mean of Wüst's values for three adjacent 5-degree parallels as being representative of the mean evaporation within each 10-degree latitude zone, his figures show an evaporation of 127.5 centimeters per year for the North Atlantic and 118.3 centimeters per year for the North Pacific. Considering the widely different methods used by Jacobs and Wüst, the high degree of correspondence between their results is remarkable.

TABLE 2.—*Average annual evaporation rates as computed by Wüst (in centimeters per year)*

Ocean	Latitude								
	0°	5°	10°	15°	20°	25°	30°	35°	40°
North Atlantic	116	105	132	145	149	140	121	107	94
North Pacific	116	102	123	128	130	127	116	106	94

McEwen (13) and Mosby (15) have computed mean annual evaporation rates from the oceans on the basis of the amount of energy available. Mosby, using recent measurements of radiation and assuming R (i. e., Q_c/Q_e) equal to 0.1, arrived at a figure of 106 centimeters per year as the average for all oceans. McEwen's computed evaporation rates for the North Pacific are presented in table 3:

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TABLE 3.—*Average annual evaporation rates for the North Pacific Ocean, as computed by McEwen (in centimeters per year)*

	Latitude						
	20°	25°	30°	35°	40°	45°	50°
Evaporation	127	122	113	107	86	66	56

Wüst's calculations showed the average annual evaporation for all the oceans to be 93 centimeters per year, and he considered this figure correct within 10 to 15 percent.

Annual Variation of Evaporation From the Ocean

Mention has already been made of the seasonal variations in evaporation as computed by Jacobs. Sverdrup (18) has computed more exactly the character of the annual variation of evaporation for a particular geographic locality by means of energy equations. Figure 6 shows his results for an area in the eastern North Atlantic located at 47° N., 12° W. The curve represents the total amount of heat given off to the atmosphere; i. e., both as sensible and latent heat. The greater part of this heat is used for evaporation so that the curve represents approximately the annual variation of evaporation. The curve shows a maximum in fall and early winter and a secondary maximum in March. In June and July no evaporation takes place; a secondary minimum occurs in February. At this locality the total evaporation during the year is about 80 centimeters.

Diurnal Variation of Evaporation From the Ocean

Since evaporation must equal the amount of water vapor which is transported upward from the surface by processes of eddy diffusion, the diurnal variation of factors influencing this process will give a clue to the character of diurnal variation of evaporation. The upward transport of water vapor depends mainly upon wind velocity, the difference between

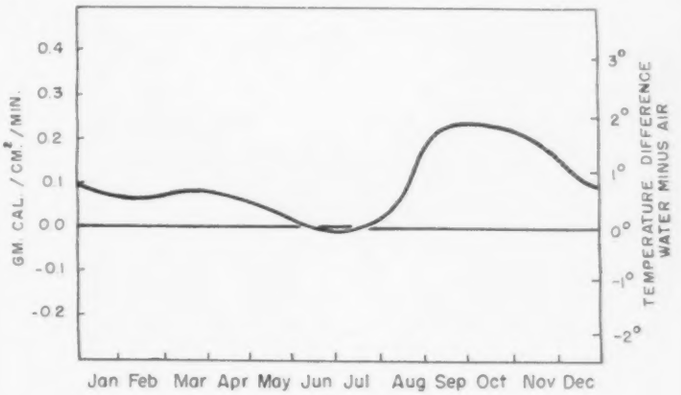

FIGURE 6.—*Character of the annual variation of evaporation.*

vapor pressure at the surface and in the air a short distance from the surface, and the state of turbulence of the air. Over the ocean, the daily variation in the former two factors is quite small, so it may be assumed that turbulence is the deciding factor.

In the Tropics, turbulence in the lower atmosphere will increase shortly after sunrise. Therefore, it is reasonable to believe evaporation will increase also. However, around noon the air temperature may become higher than that of the sea surface, so that a stable stratification ensues and evaporation will drop off during the afternoon. After sunset, when the air temperature drops below that of the sea surface, turbulence will again increase and evaporation will reach another maximum. These assumptions have been borne out by computations by Sverdrup of evaporation from data obtained near the Equator in the Atlantic Ocean. The curve in figure 7 shows the rate of heat loss from the sea surface during 24 hours. This heat loss is approximately proportional to evaporation. It is characterized by a double period with maxima in the late forenoon and the early part of the night and minima at sunrise and in the early afternoon hours.

In the trade-wind areas and in middle latitudes, the air temperature remains below that of the water. It should be expected, therefore, that evaporation would not show the double period found in the Tropics. Maximum evaporation values probably dominate during the night with a minimum in the early forenoon when the temperature difference (water minus air) is smallest.

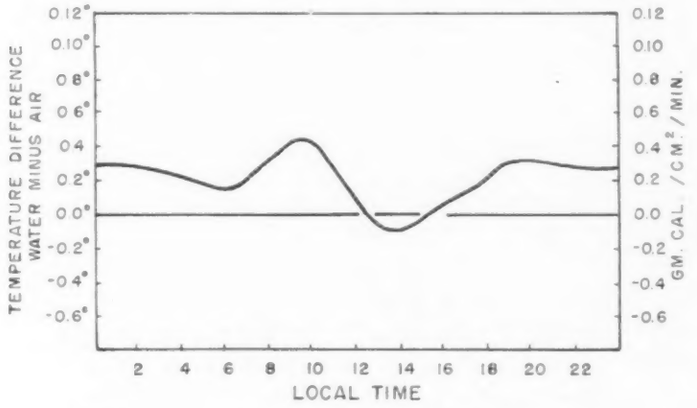

FIGURE 7.—*Character of the diurnal variation of evaporation.*

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Physical Basis of Water Supply for the United States

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Source of Moisture

Except for a small quantity of water newly created by chemical processes, the ultimate source of all moisture is the ocean. For the most part, the net amount of water available on the earth in liquid form, or as ice or snow, remains constant. Geologists have shown, however, that over long periods of time, storage in the vast reservoir of the ocean changes as water is temporarily confined in glaciers of huge proportions. Through the intricate and not yet fully understood pattern of evaporation, transport of water vapor over land, precipitation, and runoff (the hydrologic cycle), the same water is used again and again. It is, therefore, a virtually inexhaustible resource—vital to all plant and animal life, important for transportation, waste disposal, manufacturing processes, and in the production of power.

In order to use this most valuable resource with greatest benefit, as complete an understanding as possible concerning the disposition of water over continental surfaces is essential. It must be known what access various regions have to precipitation, both seasonally and annually (the *availability of precipitation*). It must be determined how precipitation varies through the year and from year to year (the *variability*). Information must be available on the occurrence of precipitation seasonally, annually, and from year to year (the *reliability*). It is further necessary that there be an understanding of the consumption of water and its use after it has started to move through or over the land.

The Transport of Water Vapor

A highly generalized picture of the large-scale circulation which would hold true if the earth had a uniform surface appears in figure 8. With the earth divided into land and ocean masses, however, and because the rates of heating and cooling differ over land and water, the idealized circulation is broken down into numerous cells of high and low pressure, as shown in figure 9. These high- and low-pressure areas vary with the season, but are fairly constant within the season (e. g., high pressure over cold land masses in winter, with low pressure over the comparatively warm water, and the reverse in summer).

Superimposed on the general seasonal circulation pattern are moving areas of high and low pressure. The areas of low pressure, also called "lows" or "cyclones," normally travel from west to east across the United States, taking a variety of paths. (See fig. 10.) The paths of lows also fluctuate with the seasons—that is, they are generally farther south in the winter and farther north in the summer.

Since the ocean is the principal source of moisture for the production of precipitation, it is not strange that most storms occur in conjunction with the mass movements of air from maritime regions. For the United States, the source areas for such air masses are the Atlantic and Pacific Oceans and the Gulf of Mexico. Thus, the major storms are intimately associated with strong flows of warm, moist air.

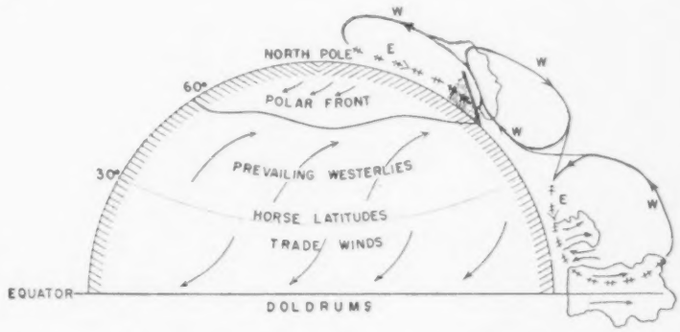


Figure 8.—*Generalized circulation in the Northern Hemisphere.*

Forces That Release Precipitation

The mechanisms which work to produce precipitation are essentially of four types. In one type of storm (fig. 11) the mountains along the west coast form a barrier to the flow from the Pacific; the air is forced to rise, and cools as it does. The moisture in the air is condensed by the cooling, and then falls as rain or snow. This type of precipitation is referred to as orographic.

Characteristic of rainfall in the eastern portion of the country is the cyclonic type of storm (fig. 12). This type of storm is a result of the interaction of two masses of air—one cold, the other warm. The boundary between these air

masses is termed a "front," and the greater the difference between the two air masses (temperature, moisture content, etc.) the sharper the front. Since cold air is denser and heavier than warm air, when the contrast between the air masses becomes sharp the front is no longer in a state of equilibrium. A wavelike ripple will appear on the front, and an area of low pressure will develop around it. The cold air usually advances faster than the warm, with the result that the warm air is lifted by the advancing front. The wave which appeared on the front earlier becomes more pronounced. As the warm air is lifted by the faster-moving cold air, it cools; the moisture condenses, and showers occur behind the leading edge of the cold air, or sometimes just ahead of it. In the northern part of the low the cold air moves parallel to the front, while the warm air advances. For lack of a place to go, the warm air rises over the cold, with precipita-

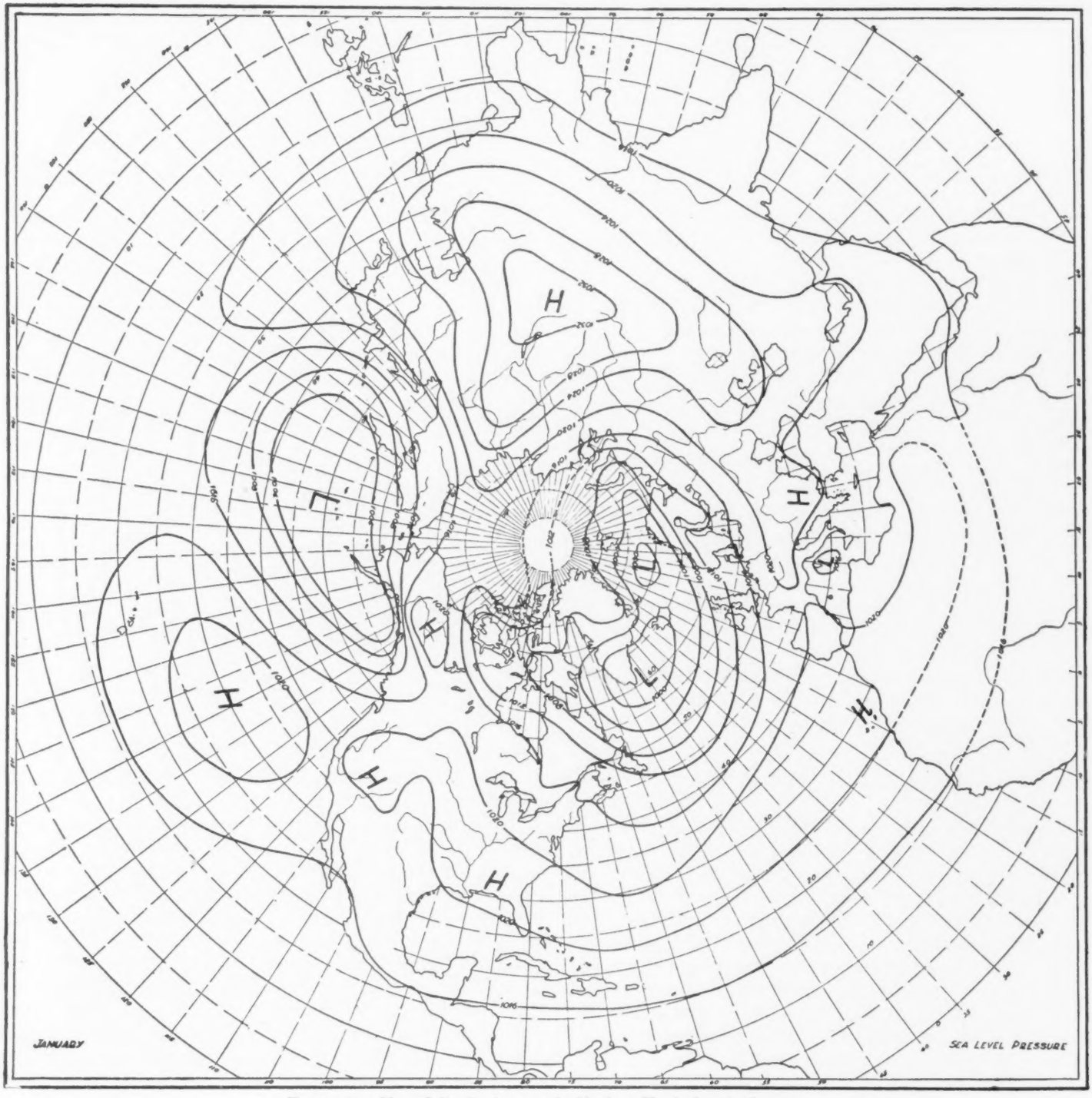


FIGURE 9.—*Normal distribution over the Northern Hemisphere in January.*

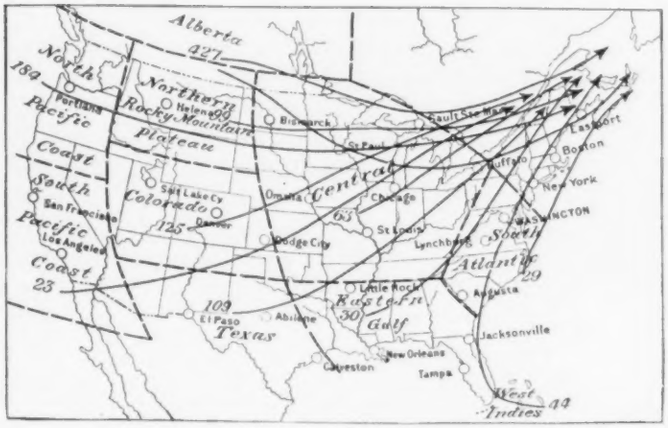


FIGURE 10.—*Average January cyclone paths.*

tion again resulting (usually in the form of steady rain or snow). The stronger the flow of warm air, the farther the area of precipitation spreads, and the heavier the rain or snow is. A model of the structure of a typical cyclonic storm is shown in figure 13.

Most of the summertime rainfall in the United States is produced by thunderstorms within an air mass. These storms are initiated by the rising of moist air which is heated excessively at the earth's surface. Strong upward air currents develop and, as other air rushes in to take the place of the rising air, an overturning motion is created. As this pattern is continued, the thundercloud builds up and finally releases its pent-up moisture in showers. This type of storm may also occur in conjunction with a weak frontal system (fig. 14).

A fourth type of storm, the hurricane or tropical storm, is prevalent during the late summer and fall months in the

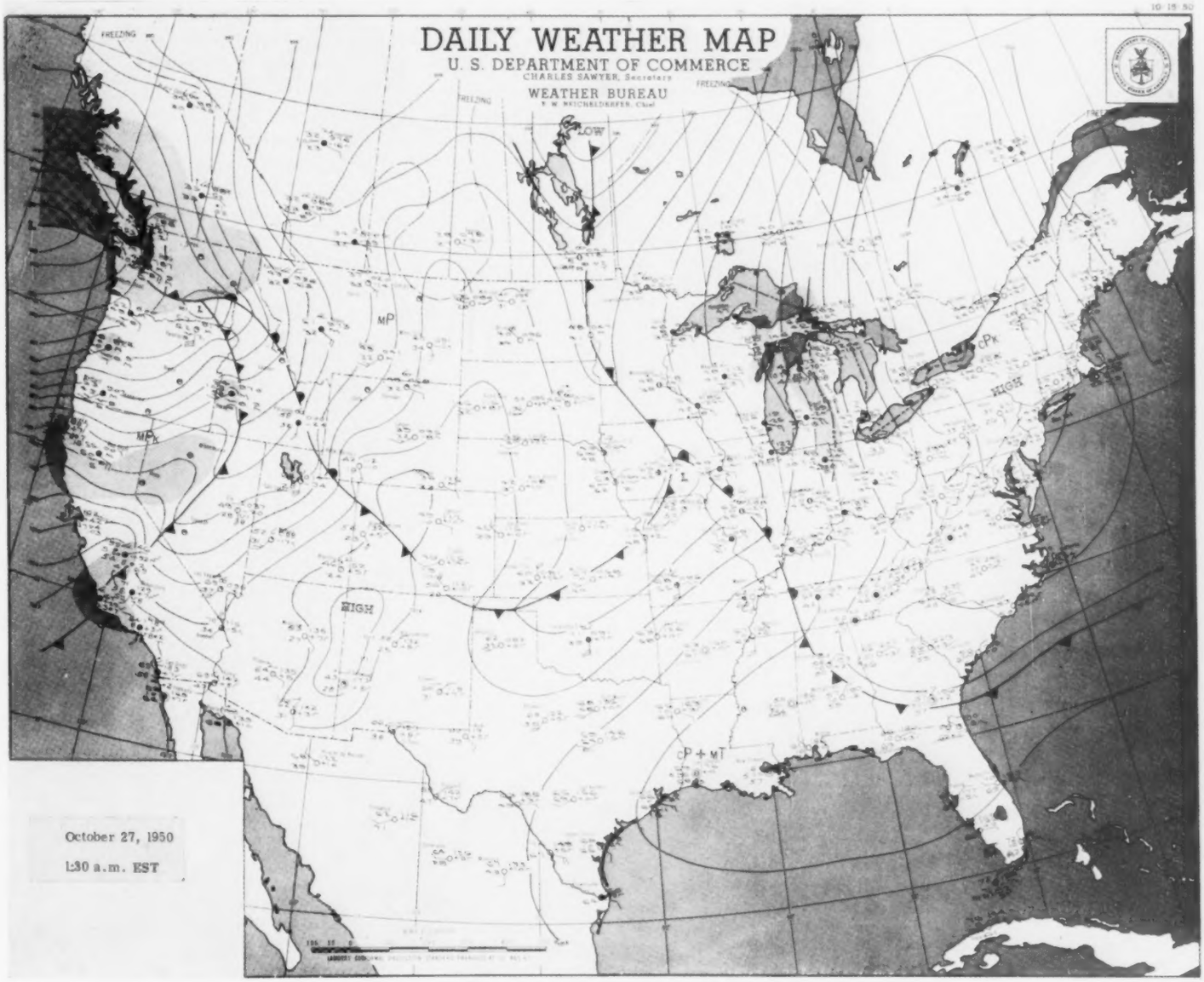


FIGURE 11.—*West Coast orographic storm.*

Gulf States and along the east coast. The tropical storm generally travels from east to west in the low latitudes, then swerves and moves northeastward as it advances into higher latitudes. In its northward movement into the higher latitudes, the tropical storm gradually loses its intensity, becoming modified as a typical cyclonic storm. The rains from this type of storm are usually steady and persistent, and the greatest amounts are generally observed near the coastal area where the storm crosses as it moves inland from the sea. The rainfall pattern associated with the hurricane of July 1916 is shown in figure 15.

Distribution of Precipitation

There are today approximately 3,000 automatic-recording rain gages in the United States. In addition, there are about 8,000 nonrecording gages where measurements are made by stick once every 24 hours. Although this may seem to be a large number of gages, it actually represents an average distribution of one gage to every 275 square miles. Over a period of years, the coverage is sufficient to determine an average amount for annual, seasonal, monthly, and even weekly precipitation (figs. 16–22). These charts are least reliable in mountain areas and in dry areas. In mountain regions sharp variations in precipitation may occur in a small area as a result of the steepness of slopes, the direction the slopes face (whether to windward or leeward), and the elevation. In dry areas, chance rainfall samplings from infrequent storms may unduly influence the averages. Also, the charts of average amounts of precipitation are also less reliable in areas where the network of rain gages is least dense.

Although average rainfall may indicate certain broad regional characteristics, the frequency of rainfalls of various intensities and the reliability of rainfall are probably most

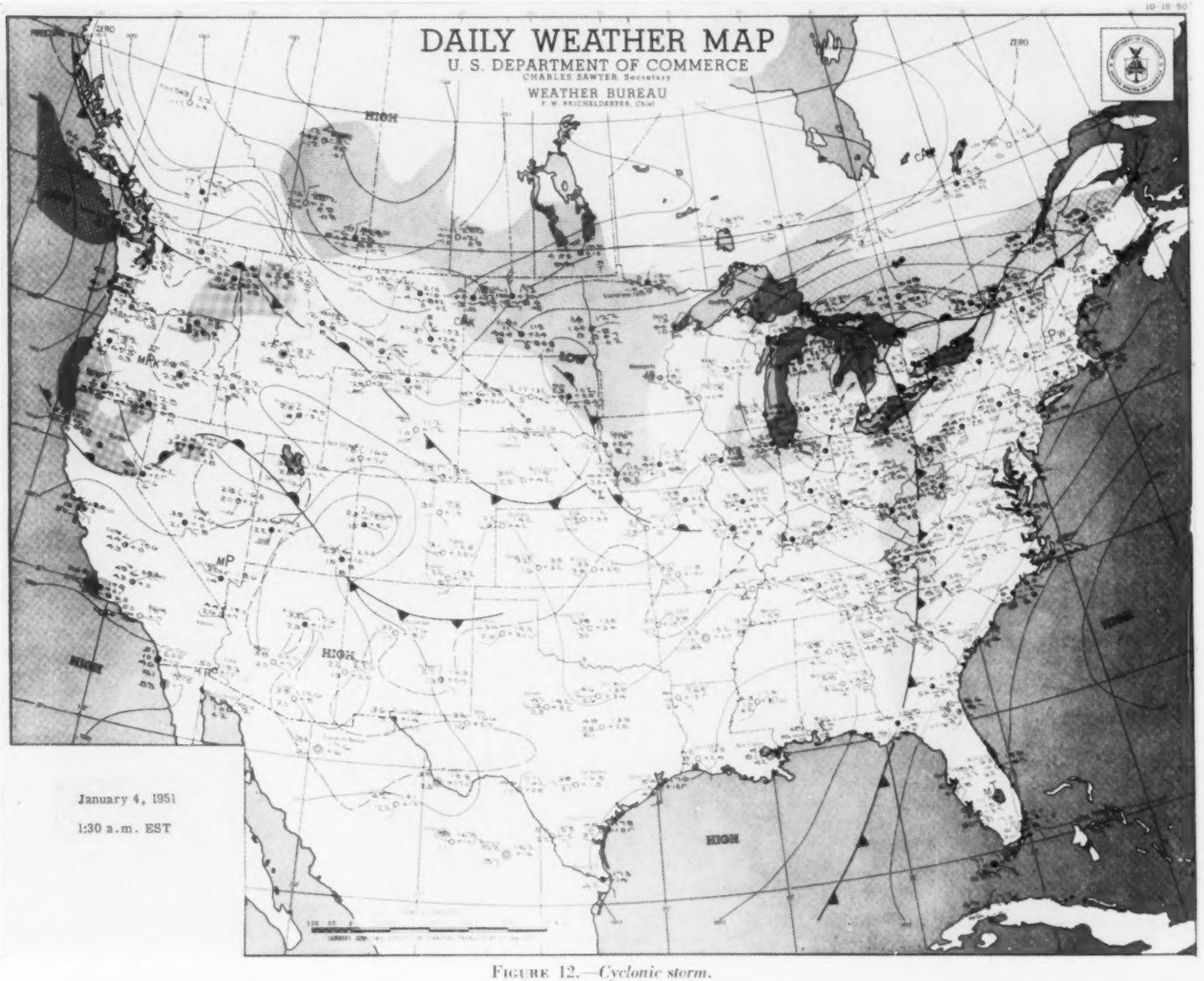


FIGURE 12.—*Cyclonic storm.*

important for an understanding of the seasonal distribution of rainfall. Generally, such charts are drawn for individual States rather than regions. Figures 23 and 24, however, showing the minimum and maximum variability of precipitation over the United States, are samples of analysis on a regional basis. Many more studies of this kind should be made in answer to specific domestic, industrial, and crop needs.

Anticipated Precipitation

Charts of the probability or expectancy of precipitation can be prepared from analyses of climatic variables when certain requirements or variables are stated. For example, if it is known that a particular crop needs a certain amount of rain during its growing period (e. g., April to June) and thereafter several months of a certain amount of sunshine, charts of the probability of occurrence of those climatic conditions in a particular region can be prepared. With the coming of machine tabulation and analysis of data, individual problems can be handled much more quickly. Certainly this type of information is invaluable in planning.

When blueprints are drawn up for the distribution of labor, or estimates made of the production and allocation of material, forecasts of amounts of precipitation for a month or more in advance would be of inestimable value. Such long-range forecasts, however, are not now possible, and even 24-hour forecasts of the areal distribution of precipitation over a river basin can still be considered in the experimental stage. This field of study gives promise of great contribution to the efficiency of farm and industrial production. The major use made of weather information at the present time, however, is not in the planning stage, but in the operational stage—*after* the precipitation has fallen.

Disposition of Precipitation as Rain or Snow

Of the precipitation which falls as a result of storms, a considerable portion does not complete the hydrologic cycle by returning to the ocean directly. Some rain is intercepted by plants, roofs, or other solid objects and soon evaporates back into the air. There is frequently a notable amount of evaporation from snow or ice surfaces. In hot dry climates, all signs of rain from a sudden shower may disappear in an hour's time—again, by evaporation. When a cyclonic storm passes, the moist tropical air associated with it is replaced by very dry polar air, and evaporation sets in at a brisk pace. The chinook, or foehn wind, which becomes warmer and drier as it descends the lee of the Rocky Mountains to the Great Plains below, has been known to melt several feet of snow in a matter of hours with scarcely any appreciable amount of water running off. The physical factors which go into determining the rate of evaporation include humidity and tem-

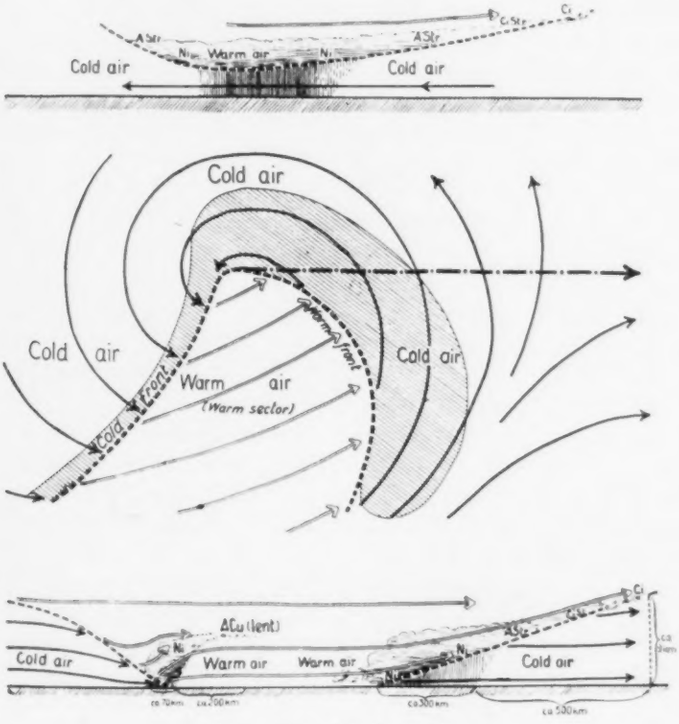


FIGURE 13.—*Idealized cyclone.*

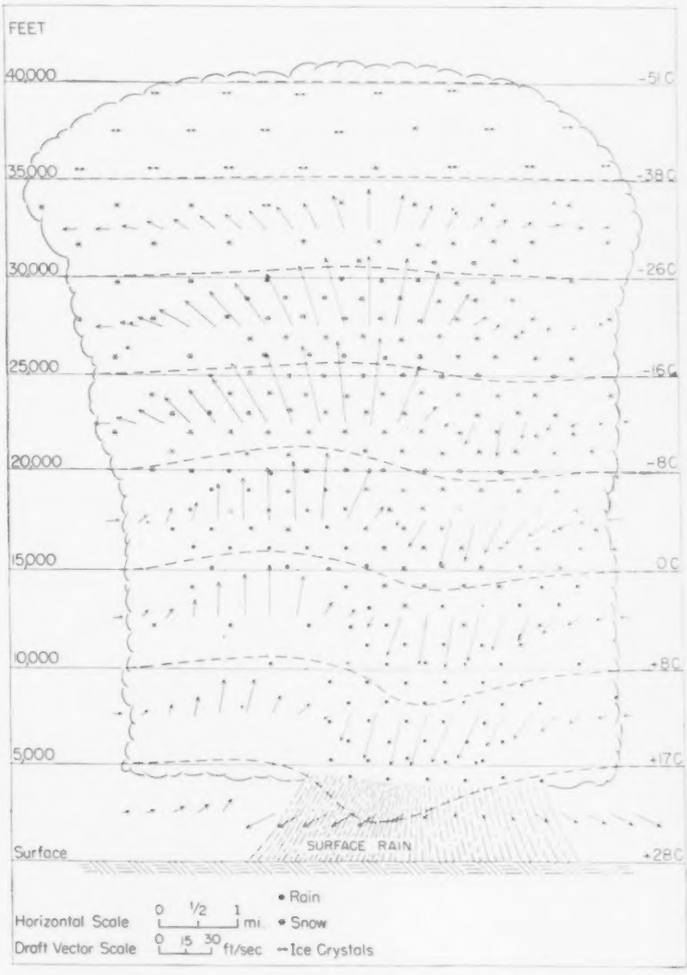


FIGURE 14.—*Mature stage of thunderstorm cell.*

perature of the air, wind speed and gustiness, barometric pressure, and the purity of the water (degree of saltiness). Figure 25 indicates the amount of moisture which would evaporate into the air over the United States annually if moisture were constantly available.

Plant life plays an important role in returning moisture to the air. The great quantity of water given off to the air by plants during the process of transpiration can only be appreciated when it is realized that several barrels of water are released into the air *each day* by a large tree in full leaf. Many experiments have been and are now being conducted in order to determine the water requirements of various types of plants during their growing period.

Part of the water falling as precipitation goes to replenish the water held in the ground, part to the deep penetration into the rocky layer below the ground level, and part as water moving through the ground layers or in underground streams. In view of these temporary losses, the hydrologist must be able to predict day by day the volume of water which flows down the river basins in order that multiple-purpose or storage reservoirs may be operated at peak efficiency. A forecast of this kind is usually the result of extensive investigations of basin characteristics as they are related to the distribution, intensity, and duration of precipitation. The condition of the ground surface of the basin before the forecast must also be given important consideration. Forecasts are usually prepared through use of multiple correlation graphs such as those illustrated in figures 26 and 27. These forecasts will be improved as the significance of additional variables is established, and as those variables are incorporated into the preparation of forecasts.

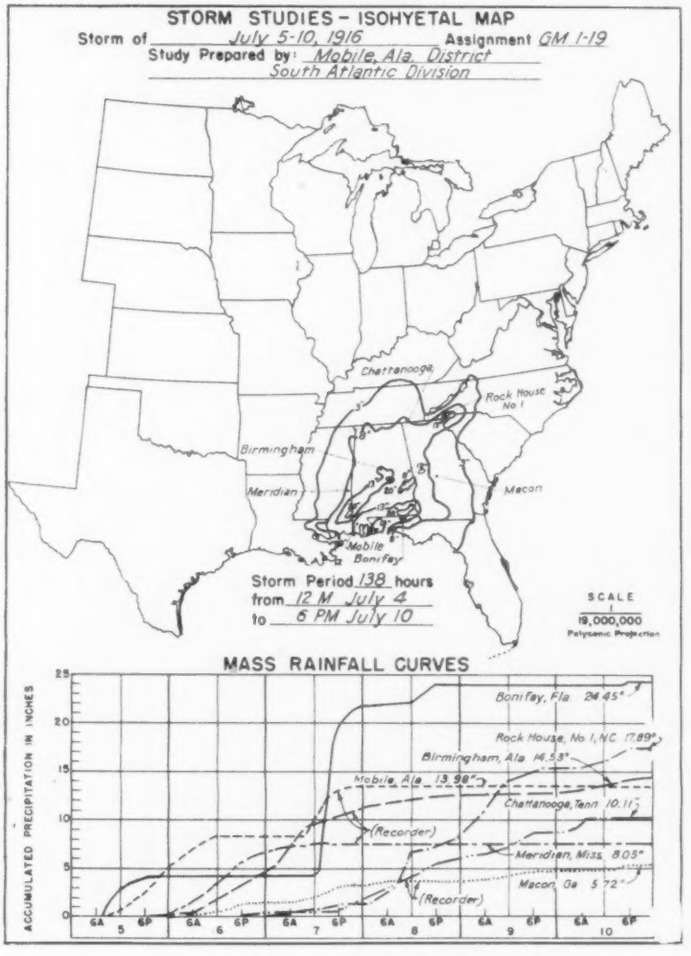


FIGURE 15.—*Hurricane rainfall, storm of July 1916.*

Artificially Induced Precipitation

During the past few years much attention has been directed to the possibility of increasing precipitation by artificial means. Experiments in the laboratory have indicated that in many cases clouds of supercooled (below freezing) water droplets tend to remain in the liquid state for considerable lengths of time. It has been found possible to convert the liquid droplets into ice particles by introduction of a cold source such as solid carbon dioxide (dry ice). Similar effects have been produced by the introduction of various chemical agents, such as silver iodide and other halogen compounds, mercury, etc.

Supercooled water-droplet clouds are also found in the atmosphere under certain conditions. During the winter months extensive decks of supercooled stratus clouds are often present. These cloud decks are rather even and regular in appearance, have limited thickness but contain only minute quantities of precipitable water. Seeding the tops of such clouds with dry ice or silver iodide converts the droplets to ice particles and often leaves a visible path or trench where the seeding has taken place. Traces of snow often fall from the cloud bases during these operations, but the amounts which reach the ground are negligible, due both to the low moisture content of the clouds and the evaporation between the cloud bases and the ground. It is generally agreed that little or no usable precipitation can be realized from seeding such clouds.

The exact mechanism by which raindrops or snowflakes are produced from tiny cloud droplets or ice particles is not fully understood. Of the many suggested mechanisms, only two have been considered to be of practical importance. The first of these is the Bergeron-Findeisen theory which requires the coexistence of ice particles and supercooled water droplets in a particular region of the cloud. As a consequence of the difference between the vapor pressure over ice and water at the same temperature, the water droplets will evaporate and condense upon the ice particles, thus tending to form larger particles. The other mechanism is the collision and resulting coalescence of drops and of ice particles. Such collisions will occur between drops or particles of different sizes falling at different speeds in the gravitational field, and can also be caused by turbulent motions within the cloud. It is currently held that in middle latitudes precipitation is generally initiated by the first process, but that once the particles have grown to some extent the second process becomes the most important. Precipitation is known to occur in the Tropics

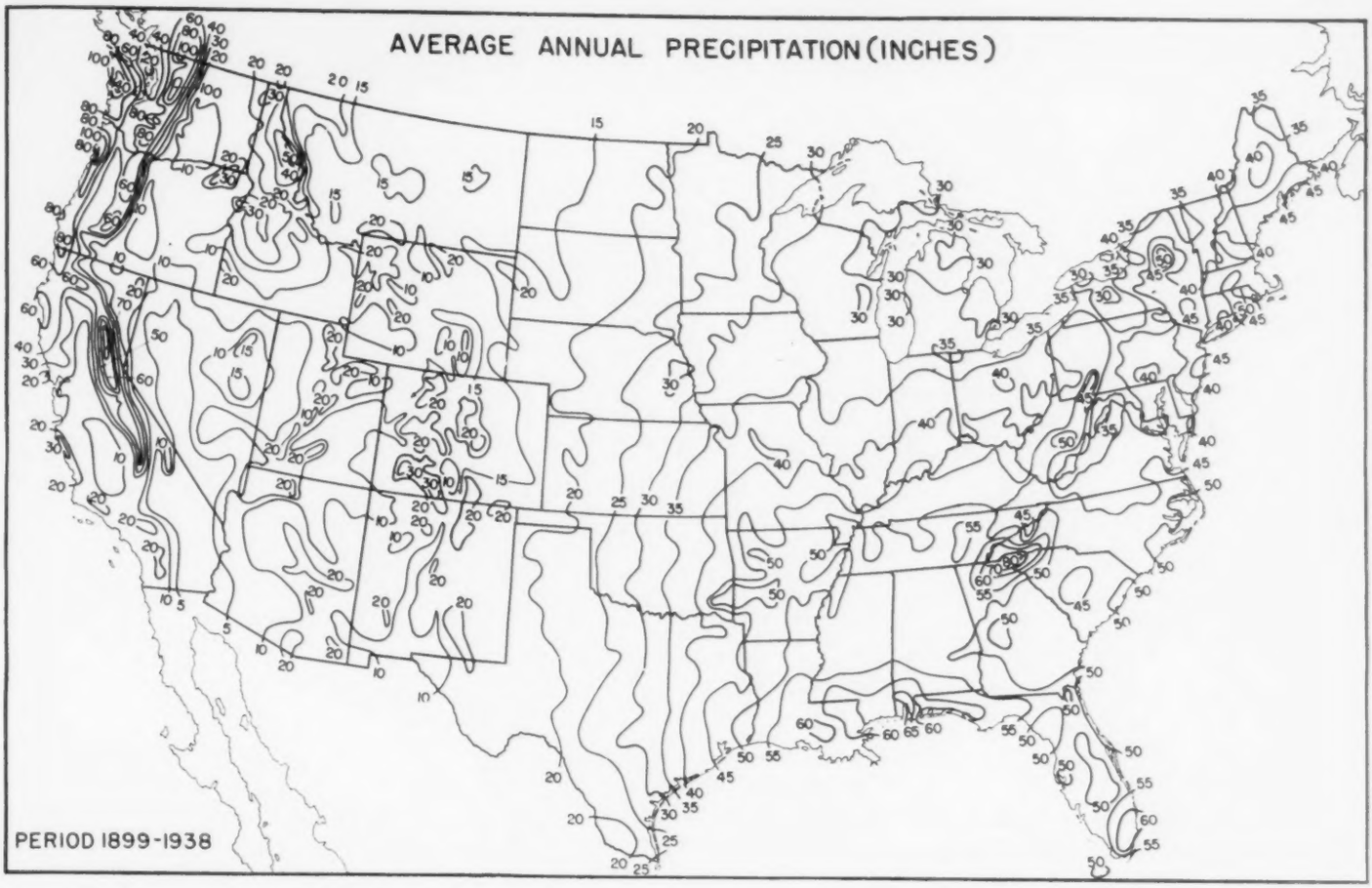


FIGURE 16 *Above.—Average annual precipitation (inches).*

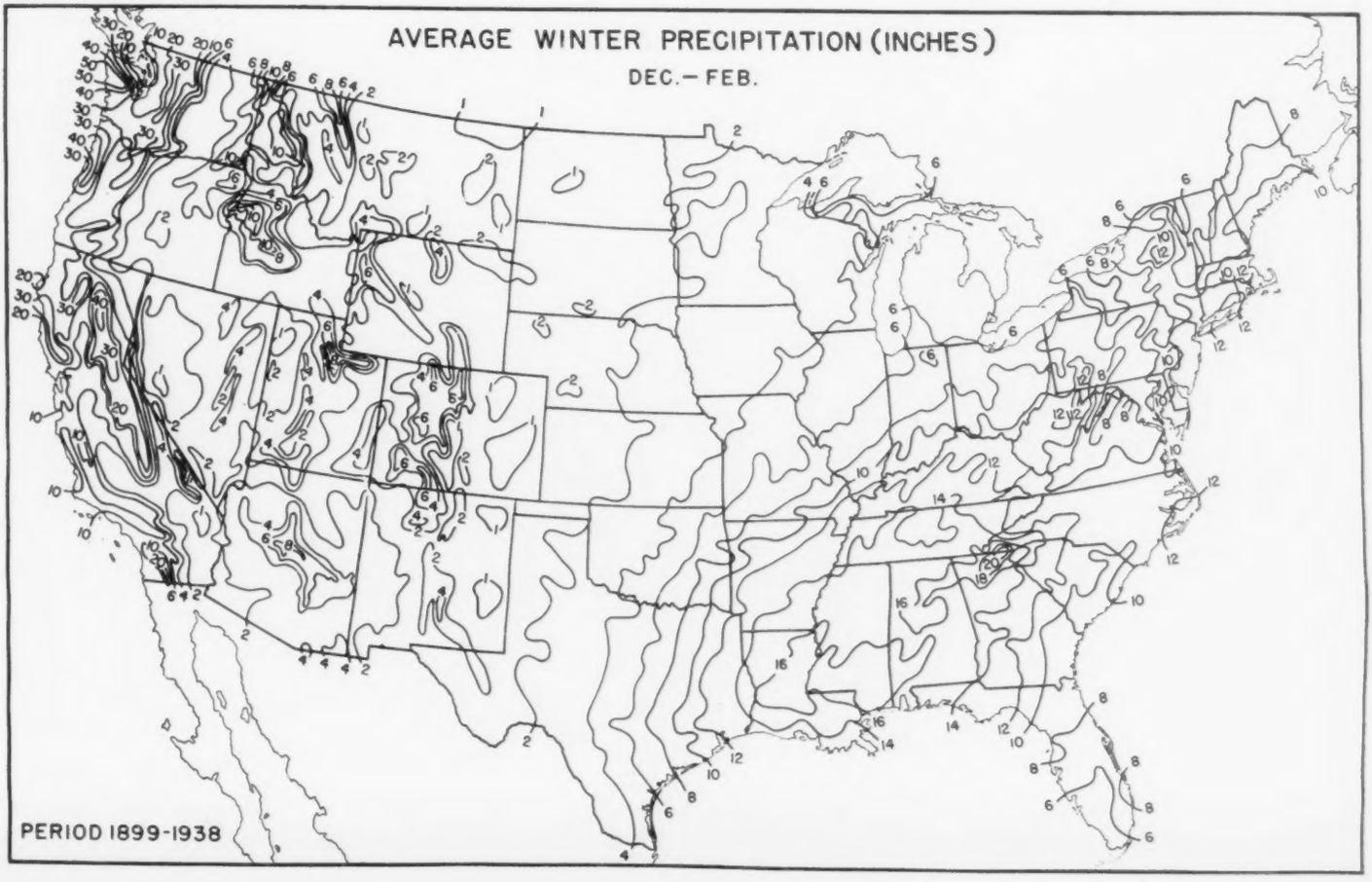


FIGURE 17 *Below.—Average winter precipitation (inches).*

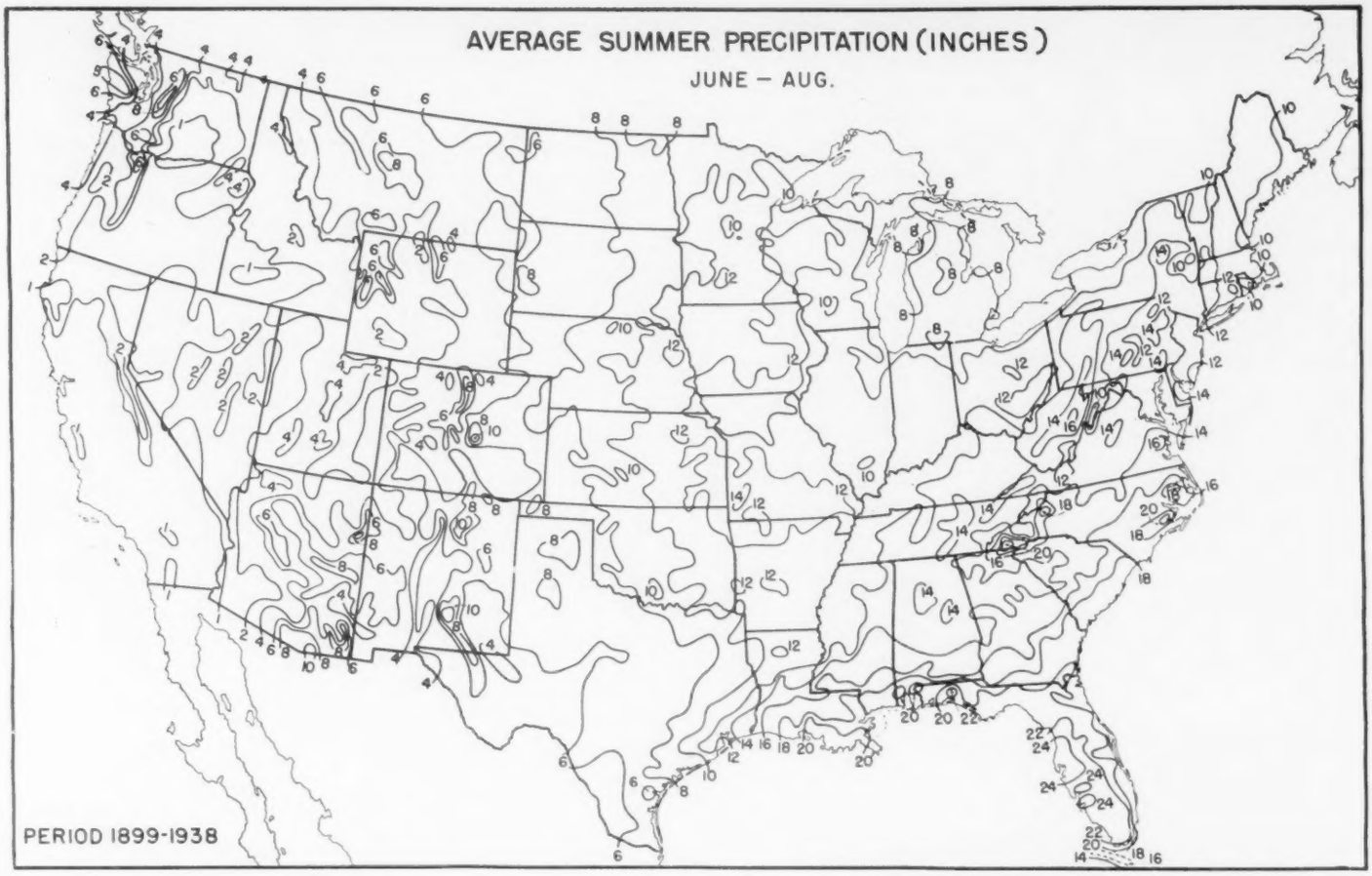
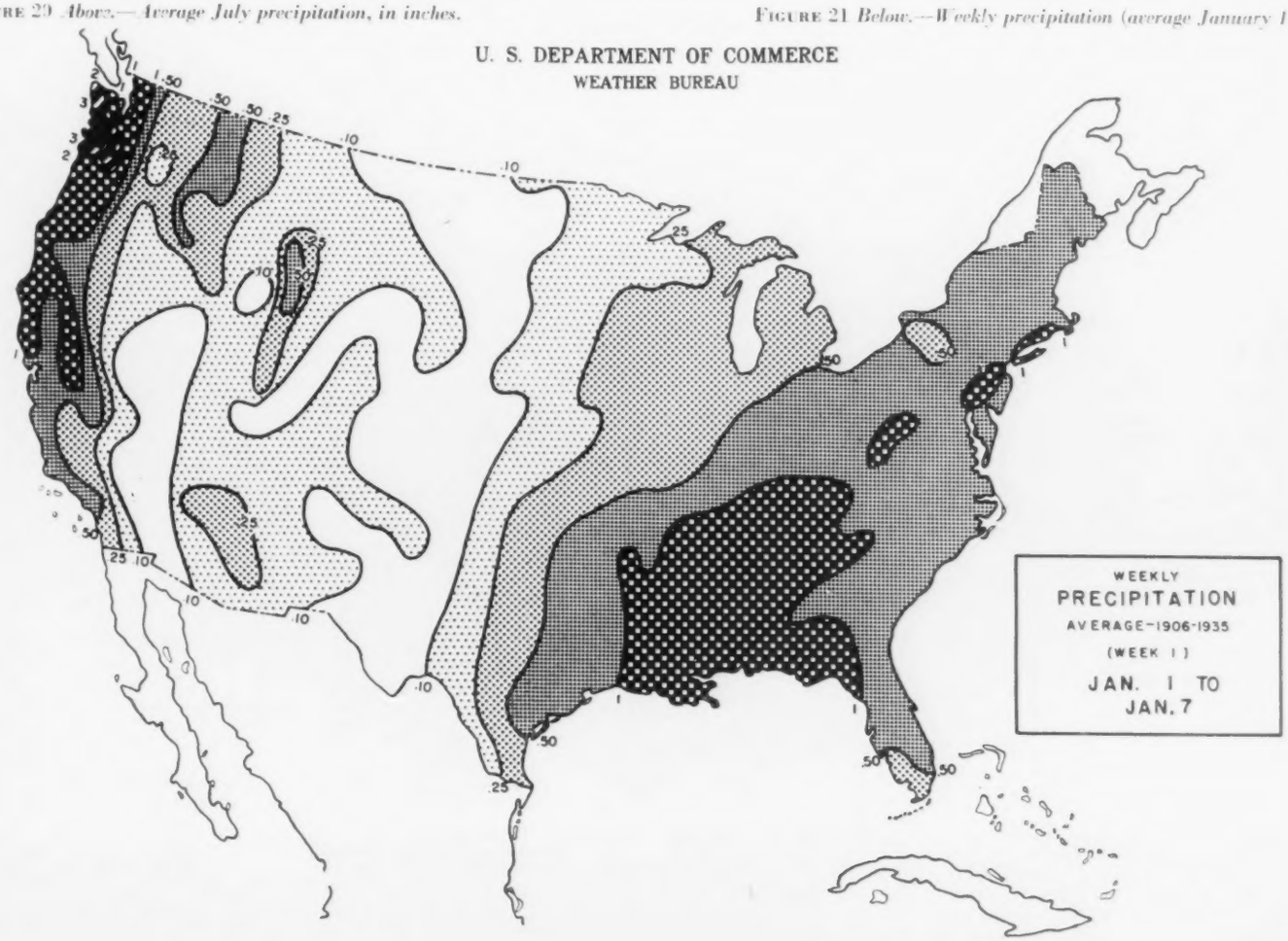


FIGURE 18 *Above.—Average summer precipitation (inches).*

FIGURE 19 *Below.—Average January precipitation, in inches*

FIGURE 20 *Above.—Average July precipitation, in inches.*

FIGURE 21 *Below.—Weekly precipitation (average January 1 to 7)*



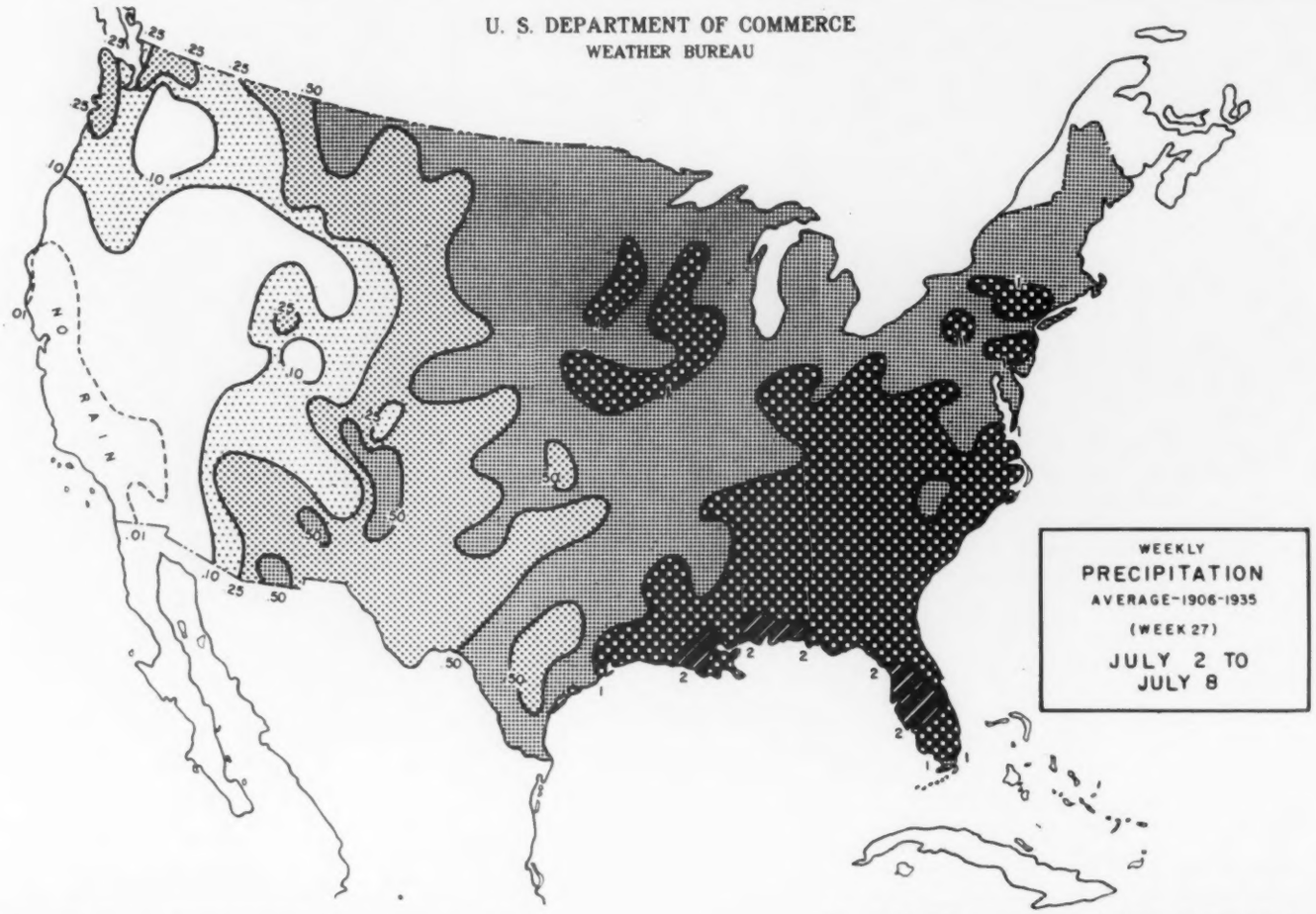


FIGURE 22 *Above.—Weekly precipitation (average July 2 to 8).*

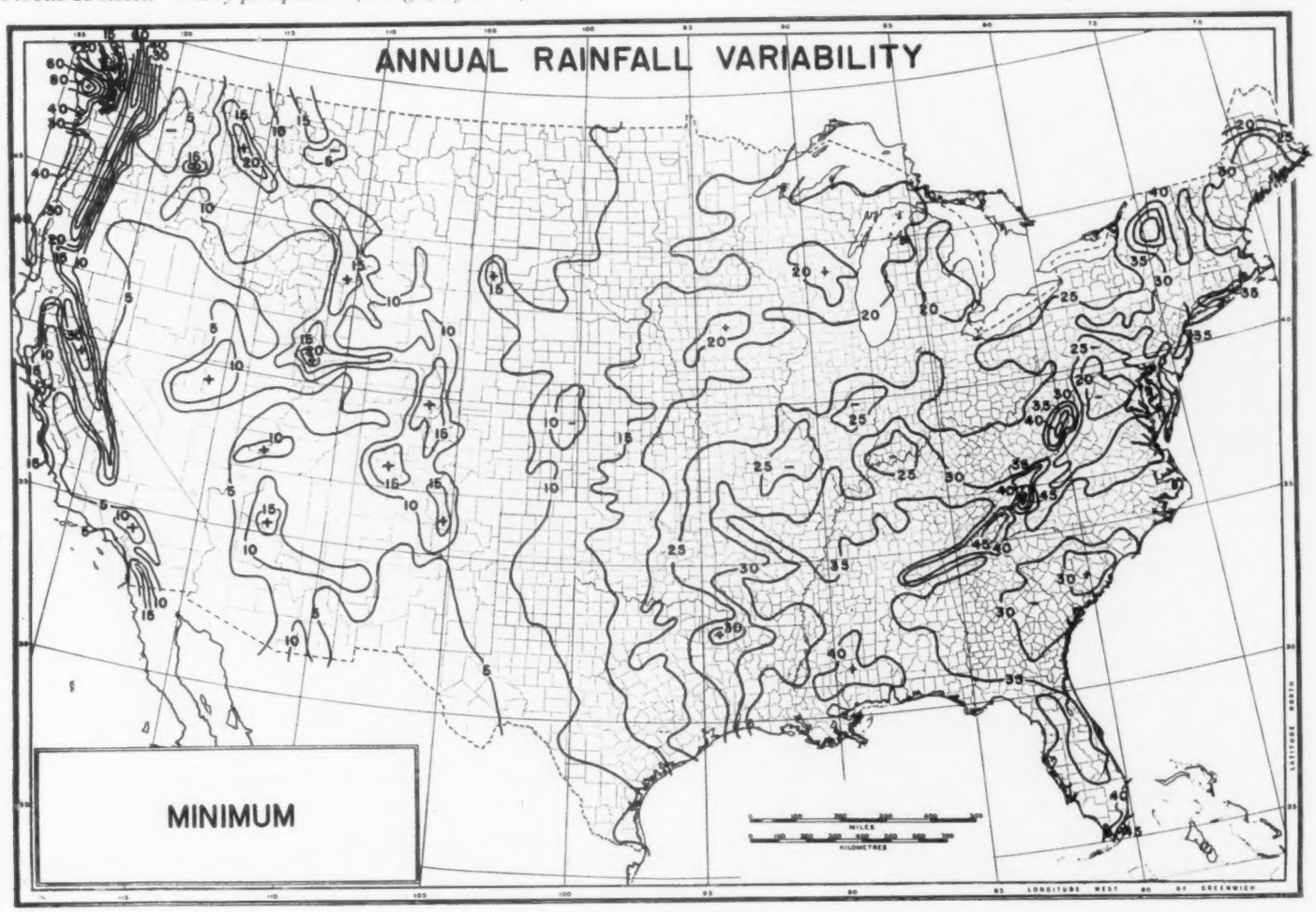


FIGURE 23 *Below.—Annual rainfall variability (minimum).*

from clouds which are not supercooled, thus indicating that the first process is not absolutely essential. The relative importance of the first process cannot be exactly determined at the present time.

The suggestion that precipitation can be increased artificially is based on the assumption that in nature there exists a substantial number of clouds capable as regards moisture content of producing important quantities of precipitation but lacking sufficient ice particles for the initiation of precipitation in accordance with the Bergeron-Findeisen mechanism. The object of cloud-seeding experiments is therefore to increase the number of such particles toward some optimum value. Since excessive numbers of ice particles, as well as deficiencies, are supposed to inhibit the initiation of precipitation, the experimenter in working with this hypothesis is faced with the problem of determining how many ice particles should be present in a particular cloud, how many will be present from natural causes, and thus how many he will attempt to supply artificially. Uncertainties arise as to the effectiveness of the various types of seeding agents in the production of ice particles, as well as to the distribution of agents released from sources on the ground. Little is known of diffusion in the atmosphere except that it is an extremely variable quantity. Also, in the case of agents released from the ground, there is the question of the longevity of the agents as effective ice-particle producers. There has been little more than speculation as to the optimum number of ice particles in particular regions of various types of clouds for most efficient precipitation. Furthermore, the natural occurrence of ice particles in clouds at various temperatures on different days in various parts of

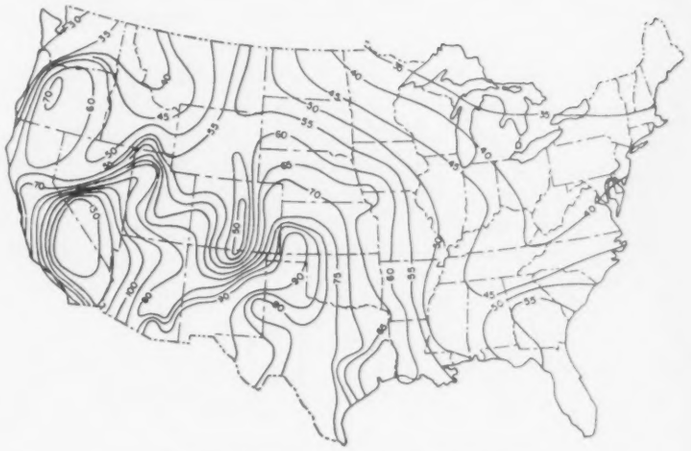


FIGURE 25.—*Normal annual evaporation.*

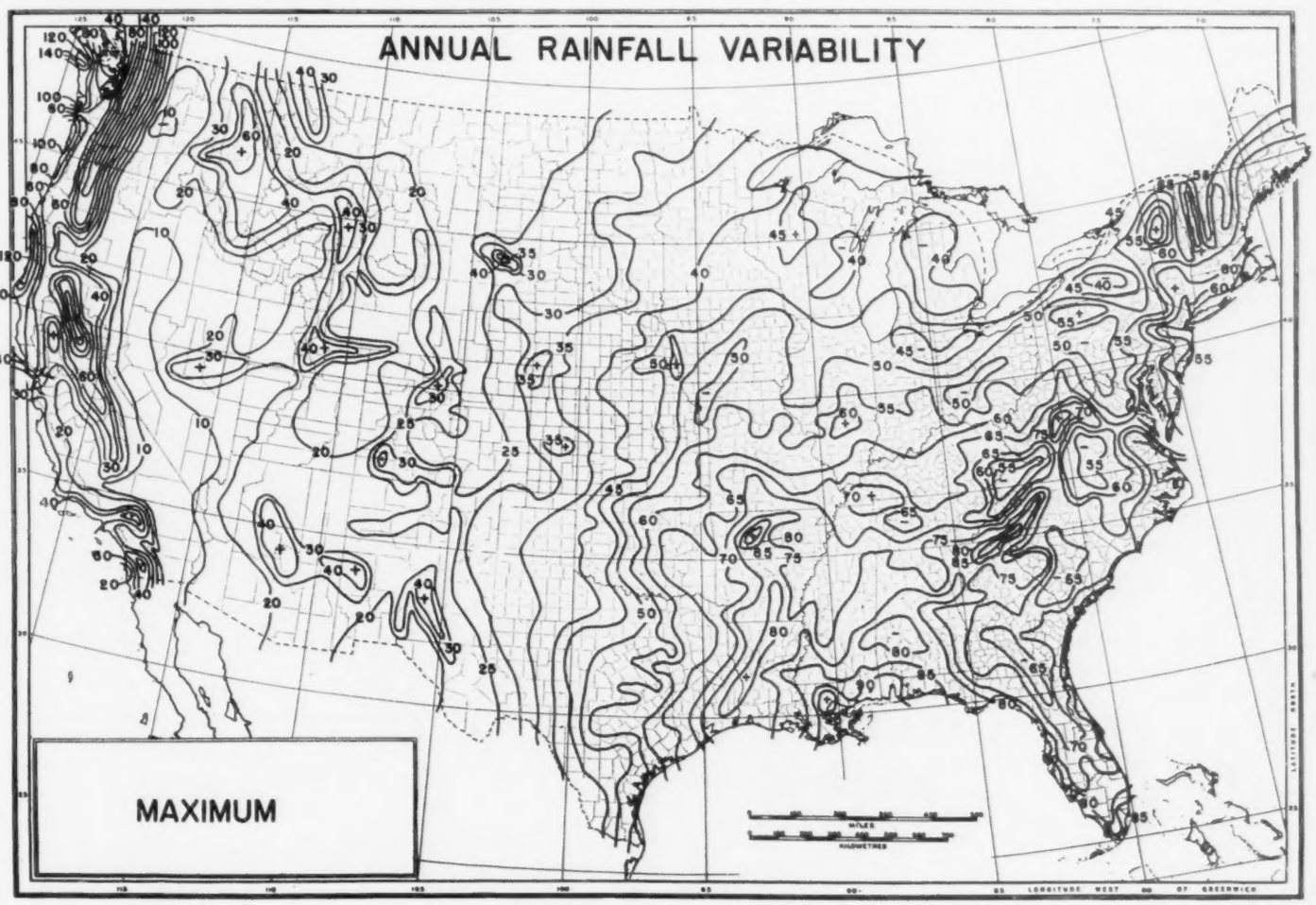


FIGURE 24.—*Annual rainfall variability (maximum).*

the country is little understood, and it is almost impossible to make intelligent estimates at the present time.

In view of the many uncertainties attendant upon present-day attempts to increase precipitation, it is difficult to speculate upon the future of cloud seeding as regards practical and general application to obtain additional precipitation in amounts economically worth while. Only very general statements can be ventured at present. Again reference is made to the uncertainties regarding the necessity or importance of ice particles in the precipitation mechanism. The general lack of substantial precipitation from seeded stratus clouds has been already mentioned. Cloud systems associated with the large-scale middle-latitude storms produce precipitation naturally without apparent difficulty, thus indicating that conditions are present for the initiation of precipitation. Cumulus clouds which do not build up sufficiently to reach temperatures where natural ice particles form in considerable quantities have been suggested as a possible untapped source of moisture. Such clouds in general have a relatively high moisture concentration and

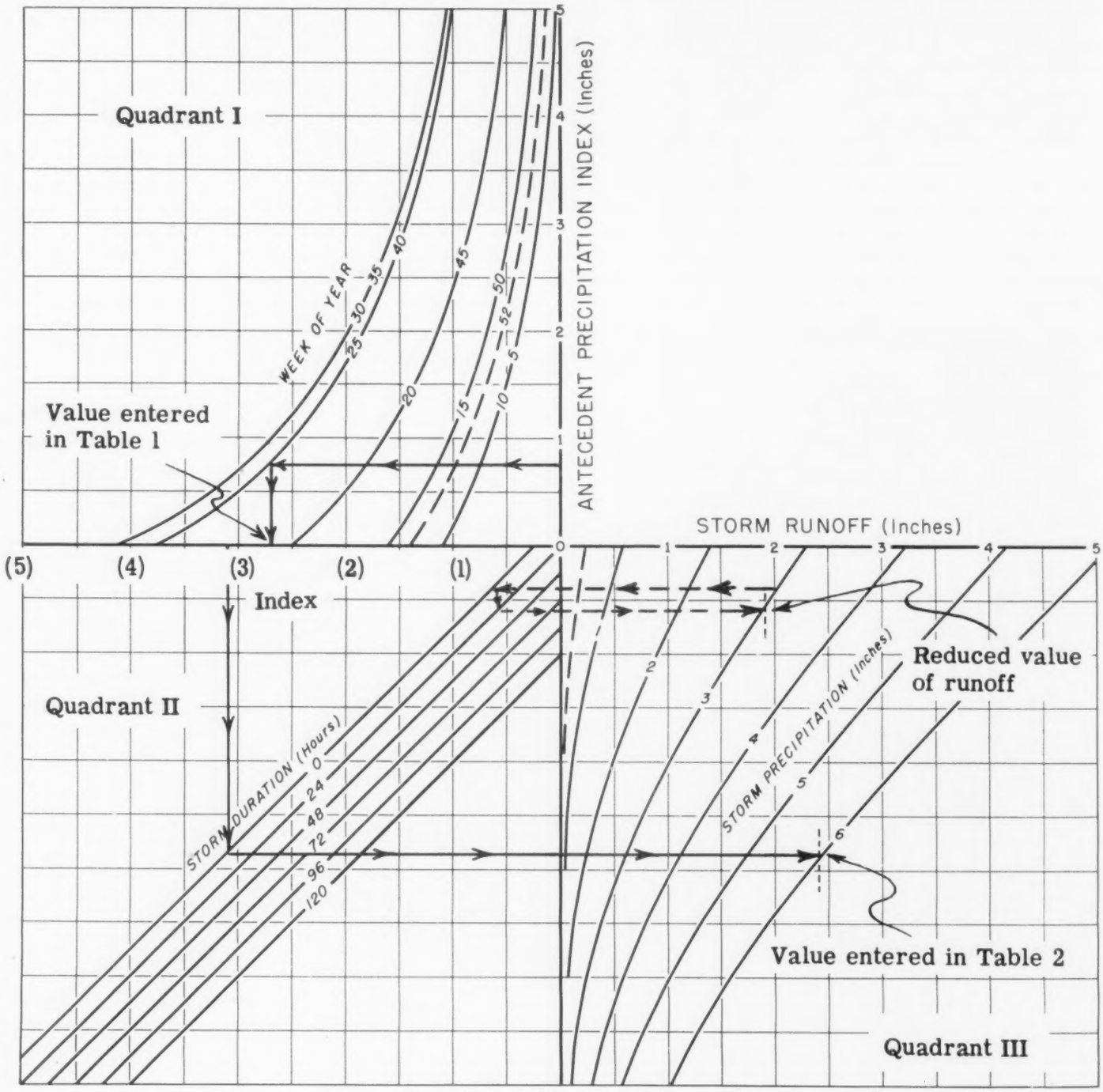


FIGURE 26.—*Rainfall—runoff relation.*

have considerable vertical development. The extent to which cloud seeding could increase precipitation from such clouds on a day-to-day basis has not been determined experimentally.

It has been suggested that snowflakes produce many additional ice crystals or particles by a fragmentation process. If this proves to be the case, it would lower considerably the number of initial ice particles required for precipitation to begin, since they would be produced by a sort of chain reaction once the process had been started. There is, in fact, some evidence supporting the belief that clouds which have been precipitating for some time are in a natural "overseeded" condition, and would require removal rather than addition of ice particles for most efficient precipitation. Such considerations also bear on the question of the possibility of inadvertently "overseeding" artificially, and of actually inhibiting precipitation.

Due both to deficiencies in our knowledge of cloud physics

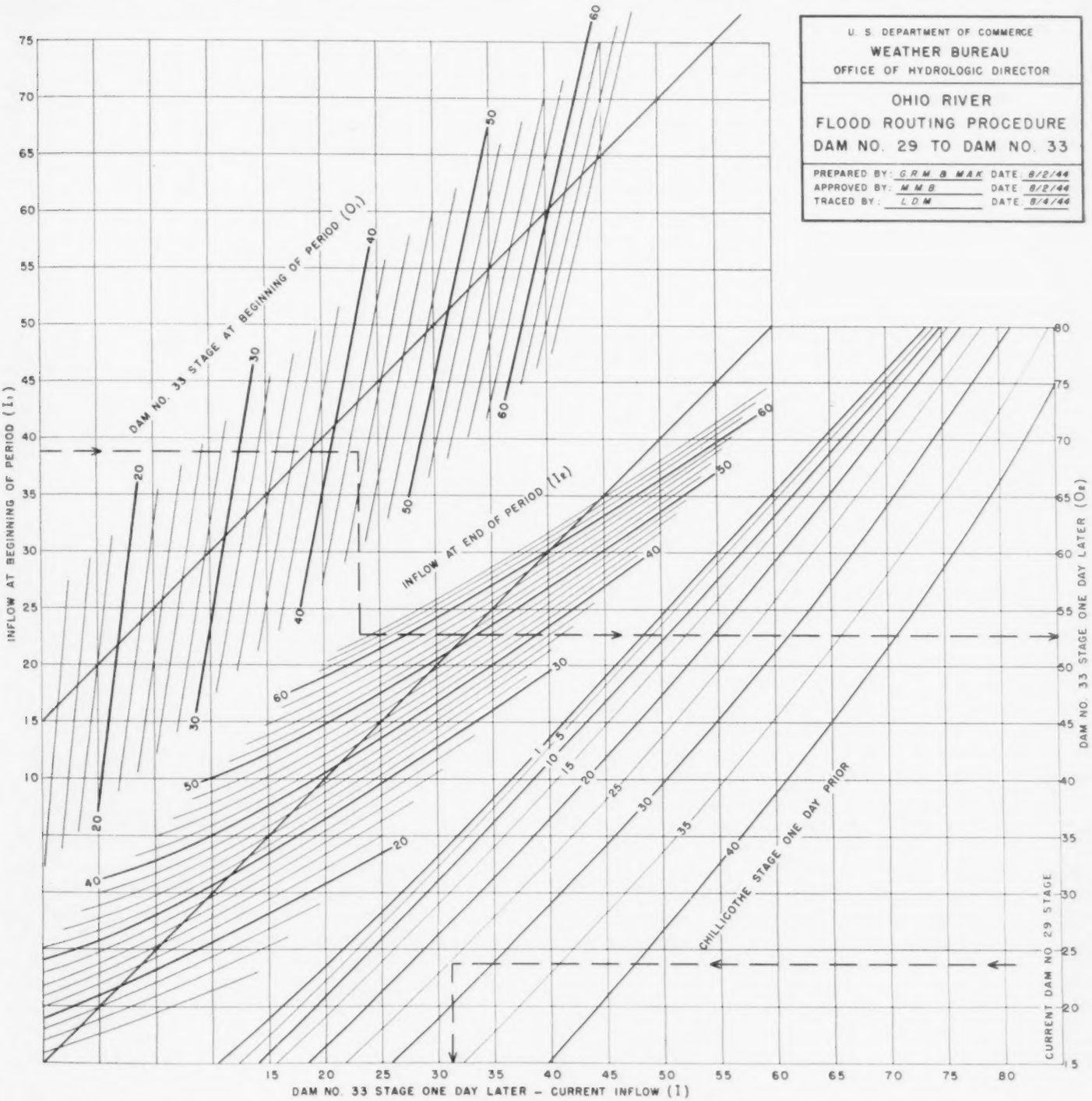

U. S. DEPARTMENT OF COMMERCE
WEATHER BUREAU
OFFICE OF HYDROLOGIC DIRECTOR
OHIO RIVER
FLOOD ROUTING PROCEDURE
DAM NO. 29 TO DAM NO. 33
PREPARED BY: G R M & M A K DATE 8/2/44
APPROVED BY: M M B DATE 8/2/44
TRACED BY: L D M DATE 8/4/44
INFLOW AT BEGINNING OF PERIOD (I1)
DAM NO. 33 STAGE AT BEGINNING OF PERIOD (O1)
INFLOW AT END OF PERIOD (I2)
CHILLICOTHE STAGE ONE DAY PRIOR
DAM NO. 33 STAGE ONE DAY LATER (O2)
CURRENT DAM NO 29 STAGE
DAM NO. 33 STAGE ONE DAY LATER – CURRENT INFLOW (I)

FIGURE 27.—*Ohio River flood routing procedure.*

and the uncertainties inherent in tests conducted in the atmosphere, the nature and magnitude of the effects of seeding on the various weather parameters including precipitation, cloudiness, temperatures, circulation patterns, etc., are undetermined. Since it does appear possible to convert supercooled cloud droplets into ice particles by dry ice or other types of seeding, the hypothesis has been advanced that there should be a resulting effect on the probability of occurrence of precipitation, as well as a discernible difference in the production, nature, and dissipation of clouds within the affected area. It has also been suggested that changes in the precipitation regime and nature and type of clouds formed may also materially affect the development of secondary and thence possibly the general circulation patterns. Since it is difficult to speculate on the degree to which any or all of these effects may exist, it is necessary at the present time to obtain estimates of such effects by actual experimentation in the atmosphere. Such experiments require statistical control in order to separate experimental results from the natural variability of the weather. Most, if not all, of the experiments thus far conducted and reported have not been designed to permit quantitative estimates of the effect, and the results are therefore inconclusive.

In the case of dry-ice experimentation, the results have been variable. Many tests have been followed by precipitation which reached the ground, the amounts generally not being measured. In many of the tests precipitation was observed to fall from the bases of clouds soon after the seeding, but to evaporate before reaching the ground. In other cases no visible precipitation was seen to fall from the seeded clouds. A majority of all cases thus far reported have failed to produce precipitation reaching the ground. In the cases where positive results seemed to have followed the seeding, some doubt appears to exist as to the number which can be definitely ascribed to the seeding and the number in which precipitation would have been released naturally. The tests were not randomized, and consequently are somewhat inconclusive on this point. There seems to be fair agreement that conditions have to be somewhat favorable for natural rain before seeding can be expected to initiate precipitation. Consequently, it is found that in many cases where the seeding has been followed by rain or snow, precipitation was also falling naturally in the same general area. In a number of cases, however, the individual investigators considered the precipitation to be unique, and consequently due to seeding.

The California Electric Power Co. has conducted a series of experiments on the crest of the Sierra Nevada Range in California in which statistical control appears adequate to permit a quantitative estimate of the effects of seeding on the precipitation falling over a particular watershed. The results of this operation are being analyzed by the power company and the Weather Bureau, and will be available in the near future.

Although it could be said that the lack of randomization has rendered a number of the tests rather inconclusive as regards scientific proof, many would undoubtedly consider the results as warranting further controlled experimentation, with provision for estimating the variability of the effect under different meteorological, climatilogical, and orographic conditions.

Experiments with silver iodide smoke released from ground generators have been attempted by project Cirrus of the General Electric Co., by the city of New York, and extensively by so-called "rainmakers" or "rain increasers," particularly in the West. The only report on this type of operation appearing in the literature is by Langmuir of project Cirrus, in which it is claimed that almost all of the rainfall on two different days in the State of New Mexico was due to silver iodide seeding. Reanalysis by the Weather Bureau of certain of these claims showed no significant results, but because of the shortness of the tests they should probably be classed as inconclusive. Preliminary analysis of the New York tests appear to indicate that long-term experimentation may be required in this and similar areas to determine seeding effects to any degree of certainty. In all of these experiments it is necessary to provide a control, that is, some means for separating out the effects produced by seeding from the natural occurrences of precipitation, etc. In many cases an adjacent area which will be relatively free from the effects of seeding can be selected, and the precipitation in this area can be used as an index of the amounts that might have fallen in the seeded area if the experiment had not been conducted. However, perfect correspondence of precipitation between adjacent areas is never found, and consequently there always remains some uncertainty as to the true effects of the seeding. The greater the natural variability, the greater the uncertainty. The size or magnitude of the seeding effect will also contribute to this uncertainty. If the effect is small and the variability large, extensive tests are required to determine the existence and size of the effect. If the effect is large, and the natural variability is small, a relatively short series of experiments will suffice.

The present outlook is that many suitably controlled experiments, probably lasting for considerable periods of time, will be required to determine quantitatively the significance of cloud seeding in augmenting the Nation's water resources, and to define the meteorological conditions favorable and unfavorable for results of practical importance.

Evapotranspiration in the Hydrologic Cycle[1]

C. W. Thornthwaite, *Director, Laboratory of Climatology, Johns Hopkins University*

Among the various climactic factors of hydrologic and agricultural significance, the return of moisture to the atmosphere from natural land surfaces is the least well known. In the form of precipitation or runoff, water is in the liquid state and can be measured by means of straightforward sampling techniques, but upon evaporating it becomes an invisible gas which mixes with the other gases of the atmosphere and is disseminated through it.

The soil is a reservoir which receives water from precipitation and from which it is withdrawn by evaporation and transpiration by vegetation. During a prolonged period without rain the soil moisture may be drawn upon until a deficiency that approaches the wilting point is produced and plant development is retarded and crop yields reduced. At the time of a storm, precipitation can partly or wholly replace the moisture that has been lost, but during the period following, evaporation and transpiration will again deplete the moisture supply. In determining drought hazard, measurement of the varying rates of evaporation and transpiration is as essential as information concerning the amount and distribution of rainfall, because they determine the rate at which the water supply is consumed.

The combined evaporation from the soil surface and transpiration from plants, called "evapotranspiration," represents the transport of water from the earth back to the atmosphere, the reverse of precipitation. The rain gage measures precipitation within acceptable limits of accuracy. We know reasonably well how rainfall varies from one place to another over the inhabited parts of the earth and also how it varies through the year and from one year to another. On the other hand, no instrument has yet been perfected to measure the water movement from the earth to the atmosphere, and consequently we know next to nothing about the distribution of evapotranspiration in space or time.

We cannot tell whether a climate is moist or dry by knowing the precipitation alone. We must know whether precipitation is greater or less than the water needed for evaporation and transpiration. Precipitation and evapotranspiration are equally important climatic factors. Since precipitation and evapotranspiration are due to different meteorological causes, they are not often the same either in amount or in distribution through the year. In some places more rain falls month after month than evaporates or than the vegetation uses. The surplus moves through the ground and over it to form streams and rivers. In other places, month after month, there is less water in the soil than the vegetation would use if it were available. There is no excess of precipitation and no runoff, except locally where the soil is impervious and cannot absorb the rain on the rare occasions when it falls. Consequently, there are no permanent rivers, and there is no drainage to the ocean. In still other areas the rainfall is deficient in one season and excessive in another, so that a period of drought is followed by one with runoff. The march of precipitation through the year almost never coincides with the changing demands for water.

Where precipitation is in excess of water need, the climate is moist. Where the water deficiency is large in comparison with the need, the climate is dry. Where precipitation and water need are equal or nearly equal, the climate is neither humid nor arid: It is called subhumid.

Potential Evapotranspiration as a Climatic Factor

The vegetation of the desert is sparse and uses little water because water is deficient. If more water were available, the vegetation would be less sparse and would use more water. There is a distinction, then, between the amount of water that actually transpires and evaporates and that which would transpire and evaporate if it were available. When water supply increases, as in a desert irrigation project, evapotranspiration rises to a maximum that depends only on the climate. This we may call "potential evapotranspiration," as distinguished from actual evapotranspiration.

We know very little about either actual evapotranspiration or potential evapotranspiration. We shall be able to measure the first as soon as existing methods are perfected. But to determine potential evapotranspiration is very difficult. Since it does not represent actual transfer of water to the atmosphere but rather the transfer that would be possible under ideal conditions of soil moisture and vegetation, it usually cannot be measured directly but must be determined experimentally. Like actual evapotranspiration, potential evapotranspiration is clearly a climatic element of great importance.

[1] The material in this paper is adapted from previously published papers of the author that are listed in the bibliography. Grateful acknowledgement is made to the editors of the Geographical Review and the Annals of the Association of American Geographers for permission to reprint selections without change and for permission to use certain maps and diagrams.

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Precipitation is a strictly physical process, which meteorologists have investigated in much detail. Evapotranspiration is likewise a physical process, yet since it is subject to biological control it must be studied by methods unfamiliar to the meteorologist. Information concerning evapotranspiration has come chiefly not from the meteorologist but from the biologist. For this reason it is necessary to make use of the literature and apply the methods of plant physiology. Nevertheless, evapotranspiration represents the return flow of water to the atmosphere and is thus an important meteorological process.

The Measurement of Evapotranspiration

The only method so far developed that measures the actual evapotranspiration from a field or any other natural surface without disturbing the vegetation cover in any way is the so-called "vapor transfer" method. Water vapor when it enters the atmosphere from the ground or from plants is carried upward by the moving air. It is carried upward in small eddies or bodies of air that are replaced by drier eddies from above. Although we cannot see water vapor, we can measure it in the air. We find that when evaporation is taking place the amount of moisture is greatest in the air near the ground and decreases with distance above it. If we determine the rate at which the air near the ground is mixing with that above it and at the same time measure the difference in water-vapor content at the two levels, we can determine both the rate and the amount of evapotranspiration. Furthermore, we can determine equally well the amount of water condensed as dew.

This method is not easy either to understand or to use. It is hard to use because it requires physical measurements more precise than are usually made. Furthermore, the coefficient of turbulent transfer of air is not a constant. It varies from time to time and from place to place. It even varies with height at a given time and place. In spite of these difficulties the method can be perfected and will answer many important questions for climatology and biology.

Scientists have tried in various ways to determine the amount of water used by plants. One of the earliest attempts was to remove leaves or branches from a plant, let them dry for a brief time, and weigh them to see how much water they had lost. Another method is to place plants in sealed containers and measure the moisture that accumulates in the confined air. Experimenters have grown thousands of individual plants in pots, weighing them periodically to determine the evapotranspiration losses. These methods are highly artificial, and generalization from them sometimes gives fantastic results. For example, in a German study transpiration from an oak woodland was computed as being more than eight times the total rainfall.

There are other less artificial methods of determining both water use and water need. In some irrigated areas rainfall, water applied by irrigation, and water outflow are all measured. The fraction of the water applied that does not run off is the evapotranspiration. In a few isolated spots, mostly in western United States, irrigation engineers have determined the evapotranspiration from plants growing in sunken tanks filled to ground level with soil in which water tables are maintained at different predetermined depths beneath the soil surface.

Since 1946 increasing thought has been devoted to the problem of measuring potential evapotranspiration and an instrument has been developed and standardized. It consists of a large soil tank so constructed that plants can be grown in it under essentially field conditions and can be provided with water as they need it. The tanks are four square meters in area and contain soil to a depth of approximately 50 centimeters. They have means for subirrigation from a supply tank designed so that actual amounts of water used can be accurately measured. In time of rain excess water drains through the soil and into an overflow tank and is similarly measured. Thus, every term in the hydrologic equation except evapotranspiration is measured. Therefore, it can be determined.

Evapotranspirometers have been installed in the Canadian Arctic, in Trinidad, near the equator, and in Tierra del Fuego near the southern tip of South America. At the end of 1950 there were four installations in Canada, one in the United States, two in Mexico, one in Trinidad, British West Indies, five in Argentina, and others projected in New Zealand, Japan, and the Belgian Congo. Continuous records since 1947 have been obtained in Toronto, Ontario, and in Seabrook, N. J.

Although the various methods of determining potential evapotranspiration have many faults and the determinations are scattered and few, we get from them an idea of how much water is transpired and evaporated and how much would be if it were available. We find that the rate of evapotranspiration depends on four things: Climate, soil moisture supply, plant cover, and land management. Of these the first two prove to be by far the most important.

Some scientists have believed that transpiration serves no useful purpose for the plant. We now understand that transpiration effectively prevents the plant surfaces that are exposed to sunlight from being overheated. Most plants require sunlight for growth. The energy of the sun combines water and carbon dioxide in the leaves into food, which is later carried to all parts of the plant and used in growth. This process, which is called "photosynthesis," is most efficient when the leaf temperatures are between 85° and 90° F. But a leaf exposed to direct sunlight would quickly become much hotter if the energy of the sun were not disposed of in some way. The surface of dry ground may reach a temperature of 200° F.; temperatures higher than 160° F. have been measured one-fourth of an inch below the ground surface.

The plant is admirably designed to dissipate heat, the leaves being like the fins of a radiator, and some of the excess heat is conducted into the adjacent air and carried away. In this way the air is heated. But some of the excess heat

energy is utilized in transpiration, to change water from a liquid into a vapor. Most of the heat of evaporation must come from the plant. Thus, the greater the intensity of sunshine, the greater will be the tendency to overheating, and the larger will be the transpiration of a plant exposed to it, if water is available for the process.

Bernard has determined the proportion of the solar energy utilized in the transpiration process in the tropical forest of the Belgian Congo. He says that direct evaporation from the soil in the virgin forest is negligible, the annual evapotranspiration consisting in part of water intercepted by the various strata of the vegetation but chiefly of the water transpired by the vegetation. By subtracting runoff from precipitation he found the annual evapotranspiration to be 139.5 centimeters. To vaporize this large amount of water an average of 223 gram-calories of heat per day is required. Since the solar energy received daily is estimated at 300 gram-calories, almost precisely 75 percent goes into the evaporation of water.

Transpiration is a heat regulator, preventing temperature excesses in both plant and air. Dew formation at night is the reverse of this process and tends to prevent low-temperature extremes, since the heat released goes mainly to the plant. Both transpiration and growth are related to temperature in the same way.

Atmospheric elements whose influence on transpiration has been studied include solar radiation, air temperature, wind, and atmospheric humidity. These factors are all interrelated. Although solar radiation is the basisc factor, there seems to be a closer parallelism between air temperature and transpiration. The temperature of the transpiring part is most closely related to the rate of transpiration.

Transpiration and growth are both affected in the same way by variations in soil moisture. Both accelerate to an optimum with increase of available water in the root zone of the soil. Above the optimum both are less, presumably because of poor aeration of the soil, which results in a lack of oxygen to supply the roots and an excess of carbon dioxide. On the other hand, as water in the soil increases above the optimum for growth, direct evaporation from the soil surface also continues to increase.

We do not yet know how much we may increase or decrease transpiration by varying the type of plants or by modifying the plant cover. Since transpiration regulates leaf temperature, and since most plants reach their optimum growth at about the same temperature, we probably cannot change it very much except by reducing the density of the plant cover and thus wasting a part of the solar energy. If all the vegetation is removed from a field, there will be no transpiration. But as long as the root zone of the soil is well supplied with water, the amount of water transpired from a completely covered area will depend more on the amount of solar energy received by the surface and the resultant temperature than on the kind of plants.

Since potential evapotranspiration is an important climatic element, we need to know its distribution over the earth and how it varies through the year and from one year to another. Actual determinations are so few that it would be impossible to make a map of any area by means of them. At the present time the only alternative is to discover a relation between potential evapotranspiration and other climatic factors for which there are abundant data.

Potential Evapotranspiration in the United States

Unfortunately, there are few controlled experiments on the relation of transpiration to temperature. The most reliable measurements of transpiration and evaporation together are for long periods of time. When only monthly or annual totals of evapotranspiration are available, the temperature relation cannot readily be determined.

The determinations from irrigation projects have shown that potential evapotranspiration is high in the southern part of the United States and low in the northern part and that it varies greatly from winter to summer. From the evapotranspirometer data it has been found that when adjustments are made for variation in day length, there is a close relation between mean monthly temperature and potential evapotranspiration. Study of all available data has resulted in a formula that permits the computation of potential evapotranspiration of a place if its latitude is known and if temperature records are available. The formula is given and its use described elsewhere.

Figure 28 shows the distribution of average annual potential evapotranspiration in the United States. It is based on normals of some 3,500 Weather Bureau stations, revised to 1930. The average annual water need in the United States ranges from less than 18 inches in the high mountains of the West to more than 60 inches in three isolated areas in the deserts of Arizona and southern California. It is less than 21 inches along the Canadian border of the eastern United States and more than 48 inches in Florida and southern Texas.

Although potential evapotranspiration and precipitation are independent climatic elements, in arid regions potential evapotranspiration is increased because of the higher daytime temperatures due to the absence of clouds and rain and because of the small actual evapotranspiration. The values in the Colorado and Gila Deserts, higher than in the tropical rain forests of Africa, are examples. In the arid section of the Columbia River Valley between Washington and Oregon the potential evapotranspiration is more than 30 inches, whereas it is only about 21 inches in the same latitude in the eastern United States.

The Water Balance

The march of potential evapotranspiration through the year follows a uniform pattern in most of the country. It is negligible in the winter months as far south as the Gulf Coastal Plain and is only 2 inches a month in southern

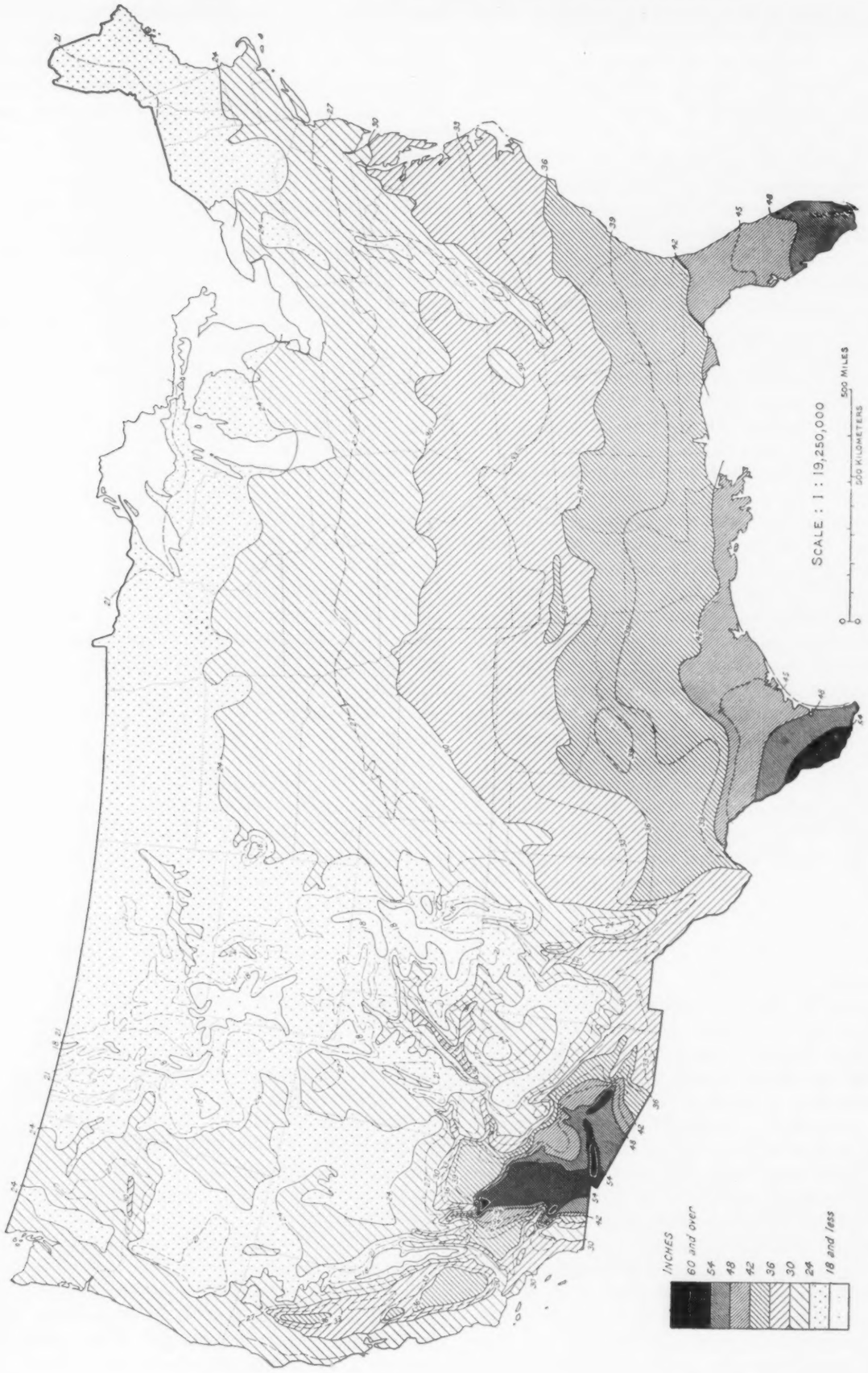

FIGURE 28.—*Average annual potential evapotranspiration in the United States.*

Florida. It rises to a maximum in July that ranges from 5 inches along the Canadian border to 7 inches on the Gulf coast. In some mountain areas and along the Pacific coast it does not reach 5 inches in any month.

The march of precipitation is highly variable from one region to another. In much of the United States more than half the rain falls in the growing season. In the Pacific Coast States the distribution is reversed, with most of the rain falling in winter. In most places the precipitation is less than the need during a part of the year. In times of excess rainfall water is stored in the soil. The part of this water that is within reach of roots is used before the plants begin to suffer.

There are very few actual observations of the amount of moisture in a soil that can be absorbed by the plants to permit optimum rates of transpiration. Comparative data for cotton, alfalfa, and orange trees growing in various types of soil are given in table 4. They are representative of data available for other soils and other kinds of vegetation. They indicate that the amount of water removed by plants from various depths of the soil depends on the distribution of active absorbing roots at different depths, which is dependent on type of soil rather than on kind of vegetation. The data in table 4 show that the water obtained from the upper foot of a sandy soil comprises only about one-third of that readily available to the plant roots, whereas the water obtained from the upper foot of a heavy clay is two-thirds of the usable water in the soil column. In all but the heaviest soils the roots ramify so completely through the upper foot of the soil that essentially all of the available moisture can be obtained. At lower depths, with less complete root ramification through the soil, a varying quantity of the available water is unobtainable. The amount unavailable to the plants varies with soil texture and depth. This results in the surprising fact that the amount of water in the root zone available to plants is nearly constant over a wide range of soil and vegetation types. Although the moisture equivalent of the soil in the above examples ranges between 32.3 and 10 percent and the wilting percentage between 16.9 and 3.5 the total water in the root zone that is available to plants ranges only between 3.90 and 4.05 inches. In shallow soils overlying bedrock or hardpan the storage capacity of usable moisture must be less than four inches. On the other hand deep, well-aerated silt loam soils may hold more than four inches of usable moisture. Nevertheless, in agricultural soils, the amount of water available to plants is far less variable than conventional studies of soil moisture would indicate.

Drought does not begin immediately when rainfall drops below the water need. Moisture that accumulates in the soil at times of rainfall excess and is within reach of roots is used before the plants being to suffer. The amount of water in the root zone available to plants varies with the soil structure and with the distribution of roots but under ordinary circumstances is equivalent to about 4 inches or 10 centimeters of rainfall. This value was used in making the curves comparing water need and precipitation at four selected stations in the United States which are presented in figure 29.

In Columbus, Ohio, the potential evapotranspiration is negligibly small in the three winter months and rises to about 6 inches in July. At the same time the precipitation is not far from 3 inches in every month. Consequently, there is too much rain in winter and too little in summer. In

TABLE 4.—*Percentage and amount of water obtained by plants from various depths in the soil*

Item	Crop	Soil	First foot	Second foot	Third foot	Fourth foot	Fifth foot	Sixth foot	Source
			Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	
1	Cotton	Heavy clay	66. 0	15. 9	6. 1	5. 2	5. 7	1. 1	[1]
2	do	Sandy loam	34. 6	27. 2	20. 7	12. 5	4. 9		[2]
3	do	Clay loam	33. 2	25. 6	17. 3	12. 6	6. 7	4. 5	[3]
4	Alfalfa	Fine sandy loam	47. 0	15. 0	15. 0	12. 0	8. 0	3. 0	[4]
5	Orange trees, mature	Sandy loam	37. 0	30. 0	15. 0	11. 0	4. 0	3. 0	[5]

Item	Field capacity	Moisture equivalent	Wilting percentage	Available water in first foot	Water obtained from—						
					First foot	Second foot	Third foot	Fourth foot	Fifth foot	Sixth foot	Total
	Percent	*Percent*	*Percent*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*	*Inches*
1		32. 3	16. 9	2. 65	2. 65	0. 64	0. 25	0. 21	0. 23	0. 04	4. 02
2	11. 0	10. 0	3. 5	1. 35	1. 35	1. 06	. 81	. 49	. 19		3. 90
3	16. 8		8. 0	1. 35	1. 35	1. 04	. 70	. 51	. 27	. 18	4. 05
4		22. 0		1. 90	1. 90	. 61	. 61	. 48	. 32	. 12	4. 04
5		15. 4	8. 8	1. 50	1. 50	1. 21	. 61	. 45	. 16	. 12	4. 05

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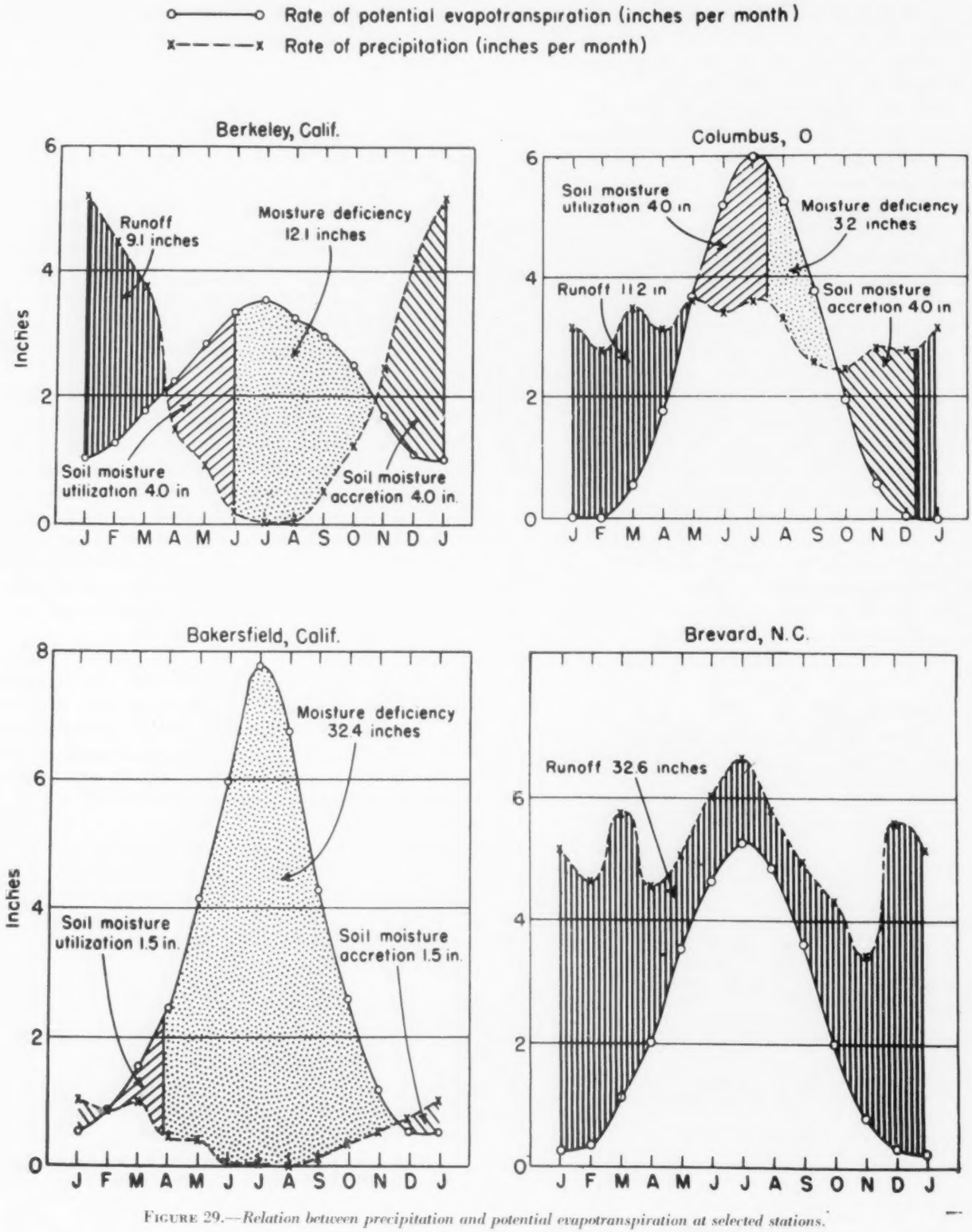
Rate of potential evapotranspiration (inches per month)
Rate of precipitation (inches per month)
Berkeley, Calif.
Runoff 9.1 inches
Moisture deficiency 12.1 inches
Soil moisture utilization 4.0 in
Soil moisture accretion 4.0 in.
Columbus, O
Soil moisture utilization 4.0 in
Moisture deficiency 3.2 inches
Runoff 11.2 in
Soil moisture accretion 4.0 in
Bakersfield, Calif.
Moisture deficiency 32.4 inches
Soil moisture utilization 1.5 in.
Soil moisture accretion 1.5 in.
Brevard, N.C.
Runoff 32.6 inches
Inches
J F M A M J J A S O N D J

FIGURE 29.—*Relation between precipitation and potential evapotranspiration at selected stations.*

midautumn, when water need falls below precipitation the surplus rainfall at first recharges the soil moisture. Thereafter it raises ground-water levels and produces surface and subsurface runoff. In spring both transpiration and evaporation increase rapidly and soon water need surpasses precipitation. At first the excess demands for water are satisfied by the soil moisture reserve. But by midsummer, when this reserve is exhausted the plants must rely solely on current rainfall and drought ensues. Although the winter water surplus is more than 11 inches, there is a summer water deficiency of 3.2 inches.

Berkeley, Calif., exhibits a relative small seasonal variation of potential evapotranspiration but a very large variation of precipitation. Consequently, the summer water deficiency is large and the resulting drought long and severe. Still there is a substantial winter water surplus.

In Brevard, N. C., every month has a surplus of rainfall. The total rainfall is more than twice the need. On the other hand, in Bakersfield, Calif., rainfall is deficient in all but the three winter months. The soil moisture recharge is only 1.5 inches during this period, however. The water deficiency in summer is more than 32 inches.

Moisture Regions in the United States

In order to obtain a moisture index the potential evapotranspiration must be compared with the precipitation. Where precipitation is exactly the same as potential evapotranspiration all the time and water is available just as needed, there is neither water deficiency nor water excess, and the climate is neither moist nor dry. As water deficiency becomes larger with respect to potential evapotranspiration, the climate becomes more arid; as water surplus becomes larger, the climate becomes more humid. Where there is a water surplus and no water deficiency, the relation between water surplus and water need constitutes an index of humidity. Similarly, where there is a water deficiency and no surplus, the ratio between water deficiency and water need constitutes an index of aridity. Since water surplus and water deficiency occur at different seasons in most places, both must enter into a moisture index, the one affecting it positively, the other negatively.

The distribution of the moisture regions of the United States, based on this moisture index, is shown in figure 30. These various hydrologic types, together with their limits are as follows:

Hydrologic type	Moisture index	Hydrologic type	Moisture index
A Perhumid	100 and above.	C_2 Moist subhumid.	0 to 20.
B_4 Humid	80 to 100.	C_1 Dry subhumid	−20 to 0.
B_3 Humid	60 to 80.	D Semiarid	−40 to −20.
B_2 Humid	40 to 60.	E Arid	−60 to −40.
B_1 Humid	20 to 40.		

The moist climates of the East and the dry climates of the West are separated by moisture index 0, in a line that extends from western Minnesota southward to the Gulf of Mexico. This is a very important line, since it separates regions of prevailing water surplus from those of water deficiency. Although dry climates predominate in the western United States, there is a belt of moist climates along the Pacific coast as far south as the San Francisco peninsula. Moist climates appear also as islands in the western mountains.

Perhumid climates are not extensive in the United States. They occur along the coasts of Washington, Oregon, and northern California and on the western slopes of the Cascades and the Sierras. There is a single small island in the high Rockies of Colorado, and other islands on high elevations in the Appalachians. A narrow belt along the Maine coast is perhumid. Humid climates are most extensive in the East, but they also occur adjacent to perhumid climates on the Pacific coast and on high areas elsewhere in the West. Subhumid climates are most extensive in the Middle West, wide belts of moist subhumid and dry subhumid extending from the Canadian border in Minnesota and North Dakota to the Gulf coast of Texas. Much of the Florida peninsula is moist subhumid. Smaller subhumid areas occur in the West, mostly as belts along the lower mountain slopes. The Great Plains and much of the intermountain region are semiarid. Arid climate is most extensive in the Southwest. There are, however, small arid areas in Washington, Oregon, Idaho, Montana, Wyoming, Utah, and Colorado. Most of the San Joaquin Valley of California is arid.

Both rainfall and potential evapotranspiration vary from one year to another. Thus the maps and curves presented above, which are made from long-time averages, tell only a partial story. Even a place like Brevard (fig. 29) may occasionally experience drought. The length and severity of summer drought in Columbus and Berkeley vary greatly from year to year. In order to determine how severe drought may be in a place, we must compare water need with water supply in individual years. In this way we can determine how often water deficiencies of various amounts take place. Figure 31 shows the water deficiencies during the 25-year period 1920–44 at four stations in agricultural areas of the United States. Comparative moisture data of these four stations are given in table 5.

TABLE 5.—*Comparative moisture data of selected stations (median values of 25-year period 1920–44)*

Station	Precipitation	Potential evapotranspiration	Actual evapotranspiration	Water surplus	Water deficiency
	Inches	*Inches*	*Inches*	*Inches*	*Inches*
Hays, Kans.	22.13	31.26	21.02	0.00	11.30
Charles City, Iowa	30.94	25.91	23.19	8.90	2.72
Wooster, Ohio	35.63	26.46	23.82	11.26	2.91
Auburn, Ala.	49.84	39.45	33.07	18.43	6.73

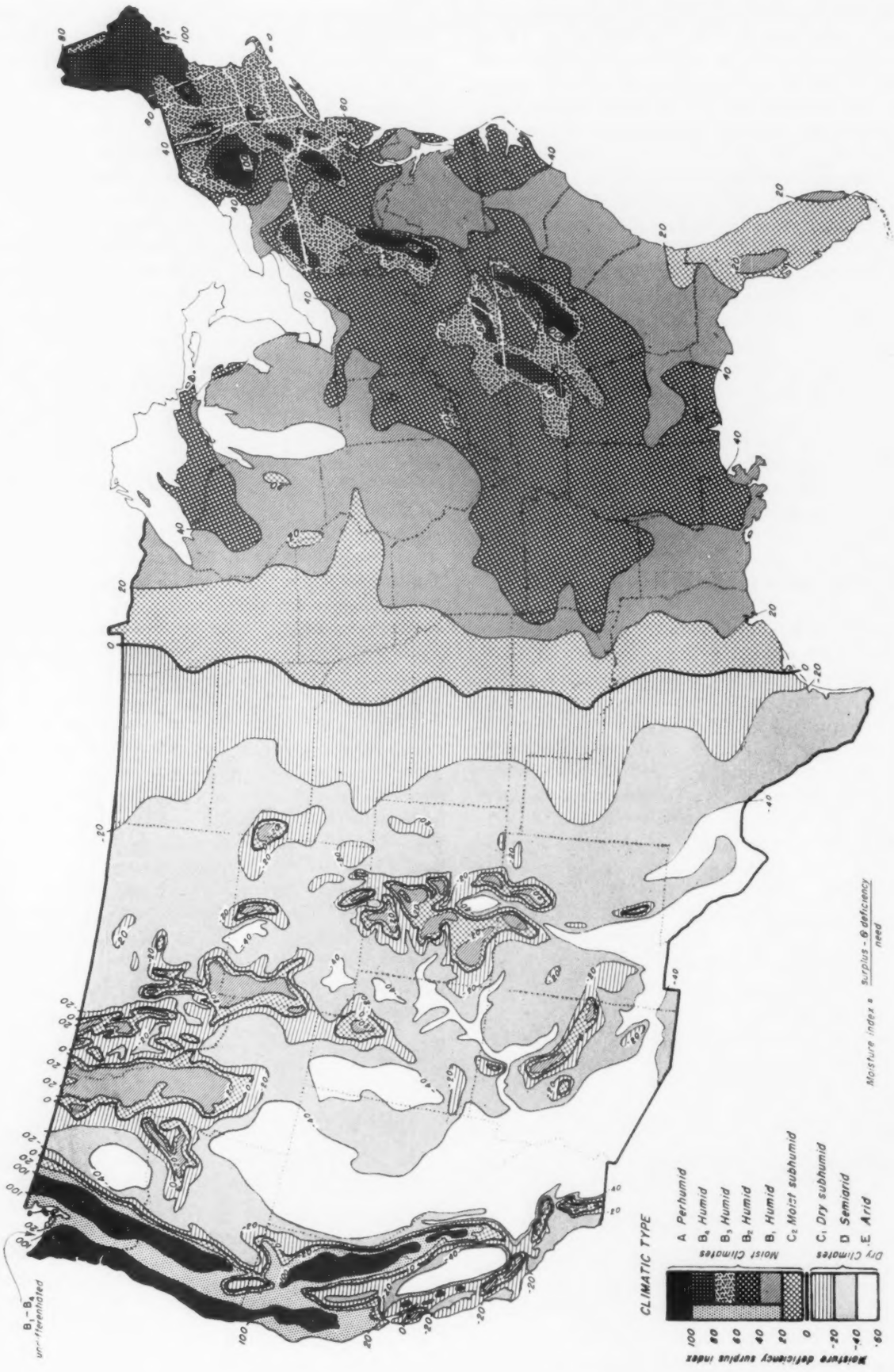

FIGURE 30.—*Moisture regions of the United States.*

In the above table, the stations are arranged in order of increasing rainfall. In Hays, Kans., the least rainy station, the rainfall of half of the years is less than 22 inches; in Auburn, Ala., the rainiest, it is more than 50 inches. In Hays the median rainfall is about 10 inches less than the need, whereas in Auburn it is 10 inches greater. In Auburn, however, much of the rainfall comes at a time when it is not needed. It becomes surplus water and flows uselessly away. The maximum annual surplus is as much as 40 inches and is more than 20 inches nearly half of the time. Thus, in Auburn, water deficiency is large. The maximum deficiency is more than 16 inches; in 20 percent of the years the deficiency is more than 10 inches; and in 80 percent it is more than 5 inches. Water deficiency is likewise large in Hays, ranging from nearly 20 inches to about 2 inches. In Hays there is not enough rainfall; in Auburn there is more than enough but it is badly distributed through the year.

In both Charles City, Iowa, and Wooster, Ohio, water deficiency is less than 5 inches in 70 percent of the years and less than 3 inches in half of the years. In Charles City it is less than 1 inch in 50 percent of the years. Drought intensity and frequency are a little smaller in Charles City than in Wooster. There is also a lower water surplus in Charles City; 8.90 inches compared with 11.26 inches. Thus, of the four stations, Charles City most nearly approaches the ideal climate for agriculture, for its water supply most nearly coincides with water need.

A Daily Water Budget

If a farmer proposes to supply supplementary water to his crops when it is needed, he must have some practical means of determining how much water to use and when to use it. Scientists have developed instruments to find out how much water the soil contains. Unfortunately, they do not yet provide the farmer with a practical means of knowing when the soil has reached a dangerous stage of dryness. Evaporation and transpiration deplete soil moisture and rainfall restores it. Thus if he knew the daily water needs of the crop and the daily rainfall, it would be a simple matter to determine day by day the extent to which the moisture reserve in the soil is being depleted. Since the water needs during a day depend mainly on the temperature and the

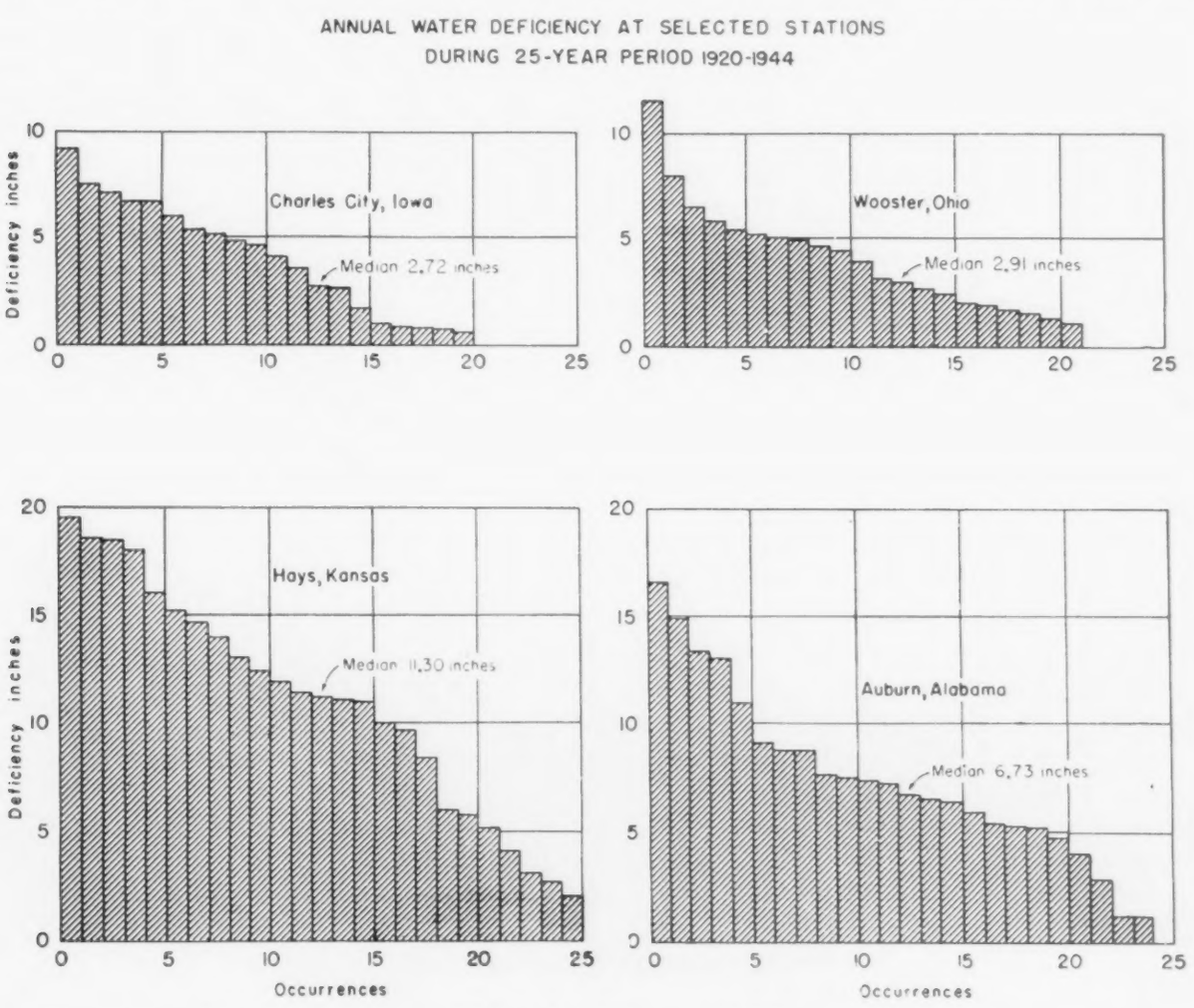

FIGURE 31.—*Annual water deficiency during 25-year period, 1920–44, at selected stations.*

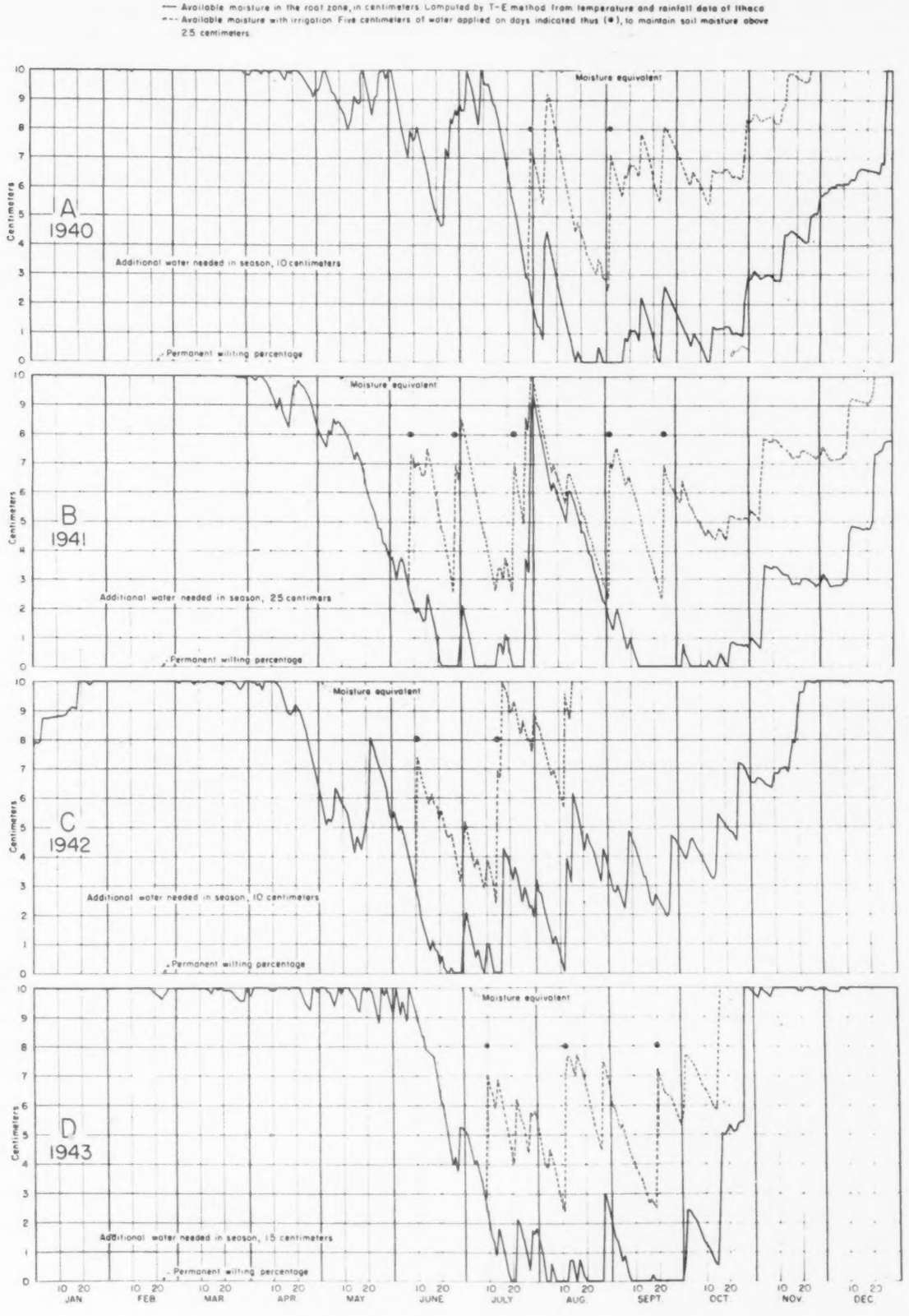

FIGURE 32.—*Soil moisture storage at Ithaca, N. Y.*

length of day, we can compute the available moisture in the root zone by the method already described. Of course, the stage of development of the crop must be considered; a newly seeded field loses water for a time only by surface evaporation.

Where a close-growing crop of perennials such as alfalfa or grass is involved, water needs not satisfied by rainfall can be determined quite accurately by computation. The computed soil moisture storage at Ithaca, N. Y., and the irrigations needed in the period 1940 through 1943 are shown in figure 32. During 8 years at Ithaca the annual water deficiency ranged between 4 and 12 inches; the average was 9.25. During 13 years at Lake City, Mich., the range was also between 4 and 12 inches, but the average water deficiency was only 7.38 inches. In order to prevent available soil moisture from falling more than 2 inches below a full supply at College Park, Md., supplemental irrigation would have been needed as follows:

Year	Number of 2-inch applications	Year	Number of 2-inch applications	Year	Number of 2-inch applications
1932	6	1937	3	1942	4
1933	4	1938	5	1943	7
1934	5	1939	8	1944	7
1935	5	1940	6	1945	3
1936	7	1941	8		

Differences in average yield of different localities are proportional to differences in drought incidence. The farmers of the East and Southeast get low returns from their work on the land partly because of high drought incidence resulting from the lack of coincidence between rainfall and water need. During much of the growing season the soil does not contain enough moisture, and in the nongrowing season a large water surplus impoverishes the soil by leaching.

To farmers everywhere drought is a serious matter. Drought is hard to measure because we are not yet able to determine very accurately the water needs of plants. We do not know when to expect droughts or how intense they may be. Therefore, we cannot be sure which moisture-conservation measures may be best at a given time and place. Droughts deserve real study. Only when we have learned how to measure evapotranspiration, both potential and actual, shall we be able to combat drought intelligently.

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A Summary of the Water Situation With Respect to Annual Runoff in the United States

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A major source of the large supplies of water of relatively low temperature and good chemical quality for municipal and industrial use in the United States is from surface runoff—water that is discharged from the land into surface streams. Runoff occurs chiefly as a residual of rainfall after Nature's take; that is, after the persistent demands of evaporation from land and transpiration from vegetation have been supplied. Except on a narrow fringe along the coasts, all excess rainfall and snowmelt drains as runoff through brooks, creeks, and rivers. This includes the outflow from ground water, in springs as well as the surface wash that follows a hard rain.

The average annual runoff of a river basin, with few exceptions, represents the limit of development of both the surface and underground water resources of the area. Any development in excess of this quantity must rely on water imported from other basins, on the using up of storage, or on the reduction of loss by evaporation and transpiration. A generalized map of annual runoff in the United States (fig. 33) presents the picture from the standpoint of total available water. The total annual discharge to the sea of all United States rivers amounts to around 1,800,000 *cubic feet* per second. About one-third of this is carried by the Mississippi River.

Interrelationships of Runoff

Runoff owes its origin, as does all fresh water, to rain or snow that has been precipitated on the continental land mass following a gaseous phase as water vapor in the atmosphere. Part of the total precipitation is locked up for long periods in ice fields and galciers, part goes into ground water that may move underground at a very slow pace or be held in storage, part is evaporated or moved by the transpiration of plants back into the atmosphere, and the rest, together with additions from percolating ground water during dry spells, runs off into streams, rivers, lakes, and finally the ocean.

Thus the Nation's streams are among our most valuable replenishable resources. As such they come in for an increasing amount of attention on the part of all governmental agencies from Federal to municipal. In the course of the last half century the trend as noted by the President's Water Resources Policy Commission in its three-volume report, is toward comprehensive development of entire river basins for multiple purposes. This involves power generation, irrigation, navigation, industrial production, sanitation, recreation, and other uses.

Measured Streams

The annual runoff represents the total flow of a stream and the upper limit of all water potentially available for development. Consequently, this figure forms a convenient unit or base for many hydrologic investigations. At the present time observations of stream flow are made regularly at about 6,300 gaging stations located on all principal rivers and on a large number of their tributaries.

Although the gaging station network covers 48 States, the density of coverage is greater along streams which are of immediate value or have large volumes of water. There are broad areas, chiefly in the West, or in the basins of small streams, where the number of stations is inadequate to give a satisfactory description of runoff.

Variations in runoff from year to year and from place to place are dominantly associated with corresponding variations in precipitation. It is most important that facts be gathered wherever such water is used or even if use is only contemplated. In addition to annual variations the total supply also fluctuates from day to day owing to transpiration, evaporation, and changes in stream flow and ground water seepage stemming from variations in precipitation.

Factors Influencing Quality and Flow

Because water is brought into contact with materials that may affect its original purity, the quality of water itself is subject to continual change and must be carefully watched. Water in motion causes erosion. Sediments in great

quantity may be transported long distances before being deposited. This is another element in water quality that needs careful study and should be taken into consideration whenever large water use is contemplated. Other factors to watch, which vary with time and alter the total supply of water in an area, include temperature, amount of solar energy, wind, relative humidity, and ground cover.

Temperature has been found to be especially important in its effect upon the itensity of the evapotranspirative processes and on the geographic distribution of runoff. A precipitation of 20 inches, for example, will result in more runoff in a region where the mean annual temperature is 50° F. than in one where the average is 70°.

Therefore the geographic distribution of average annual runoff as shown in figure 33 reflects to a high degree the variation in climate throughout the Nation. The greatest annual supply of water at any point is in the foothills of the Olympic Mountains in the State of Washington where the average runoff of the Wynoochee River at Oxbow each year is greater than 150 inches. The smallest known mean annual rainfall, on the other hand, is probably in Death Valley, Calif., where the recorded average annual precipitation at Greenland Ranch, Inyo County, amounts to less than an inch and a half.

Because annual runoff is a remainder, it fluctuates to a much greater extent than does precipitation. This is why long-period gaging of numerous rivers is necessary. Gaging provides the only means by which we can adequately evaluate our residual, usable liquid assets.

President's Water Policy Commission Findings

The importance of this work to engineers and planning agencies is apparent in the special recommendations of the President's Water Resources Policy Commission, which included advice that:

> Congress should make ample provision * * * for compilation and analysis of the necessary basic information to assure sound, comprehensive multiple-purpose basin planning. This should include geologic, hydrologic, climatic, land and soil analysis, and economic data to meet the needs of the planning agencies.
>
> Congress should require that all basin recommendations carry a precise statement as to the adequacy of the data upon which they are based * * * and should be prepared to withhold approval of recommendations in areas where the data are inadequate.
>
> A survey program designed to supply the country with full geological and hydrological knowledge of its surface and ground water resources should be initiated immediately, with ample funds for the early compilation of essential information.

How Measurements of Water Are Made

The collected discharge from a drainage basin is measured at a gaging station in cubic feet per second. However, it has become customary to express volume of runoff in terms of inches of water over the drainage area. This is done in order to facilitate comparison with other basins and with rainfall, and to simplify other hydrologic studies.

The total volume of water discharged, when divided by the drainage area, yields a quotient expressible in inches, which indicates the mean depth contributed by the drainage basin. Quite naturally, this does not signify that each unit of area drained contributed equally. The depths of runoff contributed by each unit of area may differ because of variation in precipitation over the whole basin or because of geology and topography.

Importance of Wise Water Use

Generally speaking, water is at a premium in those areas where the average annual runoff is less than 1 inch. However, a yearly runoff of one inch represents a yield of more than 17,000,000 gallons from each square mile. This is about 48,000 gallons per day, or 53 acre-feet for the year. If properly managed, the runoff from 1 square mile having only half an inch of annual runoff would normally irrigate about 10 acres of cropland or supply domestic water for about 150 people.

Some parts of the areas shown in figure 33 to have less than 1 inch of runoff are potentially the most productive agricultural land in the country. A vast acreage of fertile land in those areas is irrigated through the use of surface water brought from nearby areas by regulation of natural stream flow or by diversion through man-made canals.

Table 6 was prepared to show the areal distribution of runoff in the United States. The amount of annual runoff is less than 5 inches over more than half the country.

TABLE 6.—*Mean runoff, precipitation, and evapotranspiration in the United States*

Range in runoff (inches per year)	Area [1] (square miles)	Percent of total area	Percent of total runoff
0 to 0.25	306,000	10.1	0.1
0.25 to 0.5	380,000	12.6	.5
0.5 to 1.0	266,000	8.8	.8
1.0 to 2.5	413,000	13.7	2.8
2.5 to 5	247,000	8.2	3.6
5 to 10	258,000	8.5	7.4
10 to 20	830,000	27.4	44.8
20 to 40	290,000	9.6	32.4
40 to 80	30,000	1.0	6.9
Over 80	2,000	.1	.7
Total	3,022,000	100	100

Geological Survey data show the total volume of runoff in areas of external drainage to be 26,000,000 square-mile inches. Dividing this figure by the total area of the country (3,022,000 square miles) indicates that the Nation-wide runoff in the period from 1921 to 1945 averaged 8.6 inches. The difference between the average rainfall, 30 inches, and

the annual runoff, 8.6 inches, is 21.4 inches. This difference represents the amount of water lost to the atmosphere through evaporation and the transpiration of plants. Figure 34 indicates the distribution of precipitation, runoff, and evapotranspiration by major drainage basins.

Although it is quite generally believed that all the rivers run into the sea, yet about 8 percent of the land area of the United States drains into arid interior basins where salt or brackish lakes, playas, or alkali flats dispose of the water by evaporation and transpiration. The largest of these is the Great Basin. This vast area, some 215,000 square miles, discharges no water into the oceans. Therefore, all the precipitation that falls within the Great Basin eventually returns to the atmosphere.

Estimated Flow to the Oceans

Summarizing estimates of flow to the oceans from various regions, the total runoff adds up to about 1,800,000 cubic feet per second, which is equal to 8.1 inches which compares quite closely with the 8.6 inches previously mentioned.

The difference results from a combination of two factors: (1) evaporation losses from the water surface of rivers and (2) incomplete evaluation of the area of interior drainage (the noncontributing areas).

TABLE 7.—*Estimated flow to the oceans*

Description	Area (square miles)	Mean annual flow	
		Cubic feet per second	Millions of acre-feet
North Atlantic slope basins	149,000	210,000	152.0
South Atlantic slope and eastern Gulf of Mexico basins	285,000	325,000	235.3
Mississippi River Basin	1,250,000	620,000	448.9
Hudson Bay basins	48,000	5,000	3.6
St. Lawrence River Basin	130,000	140,000	101.4
Western Gulf of Mexico basins	320,000	55,000	39.8
Colorado River Basin	246,000	23,000	16.7
Great Basin	215,000	0	0
Pacific slope basins in California	117,000	80,000	57.9
Columbia River Basin and coastal streams in Oregon and Washington	262,000	345,000	249.8
Total	3,022,000	1,803,000	1,305.4

Climate and Seasonal Effects

Variation in annual runoff is dominantly associated with climate, chiefly precipitation and temperature. Temperature is important because it determines the amount of the evapo-

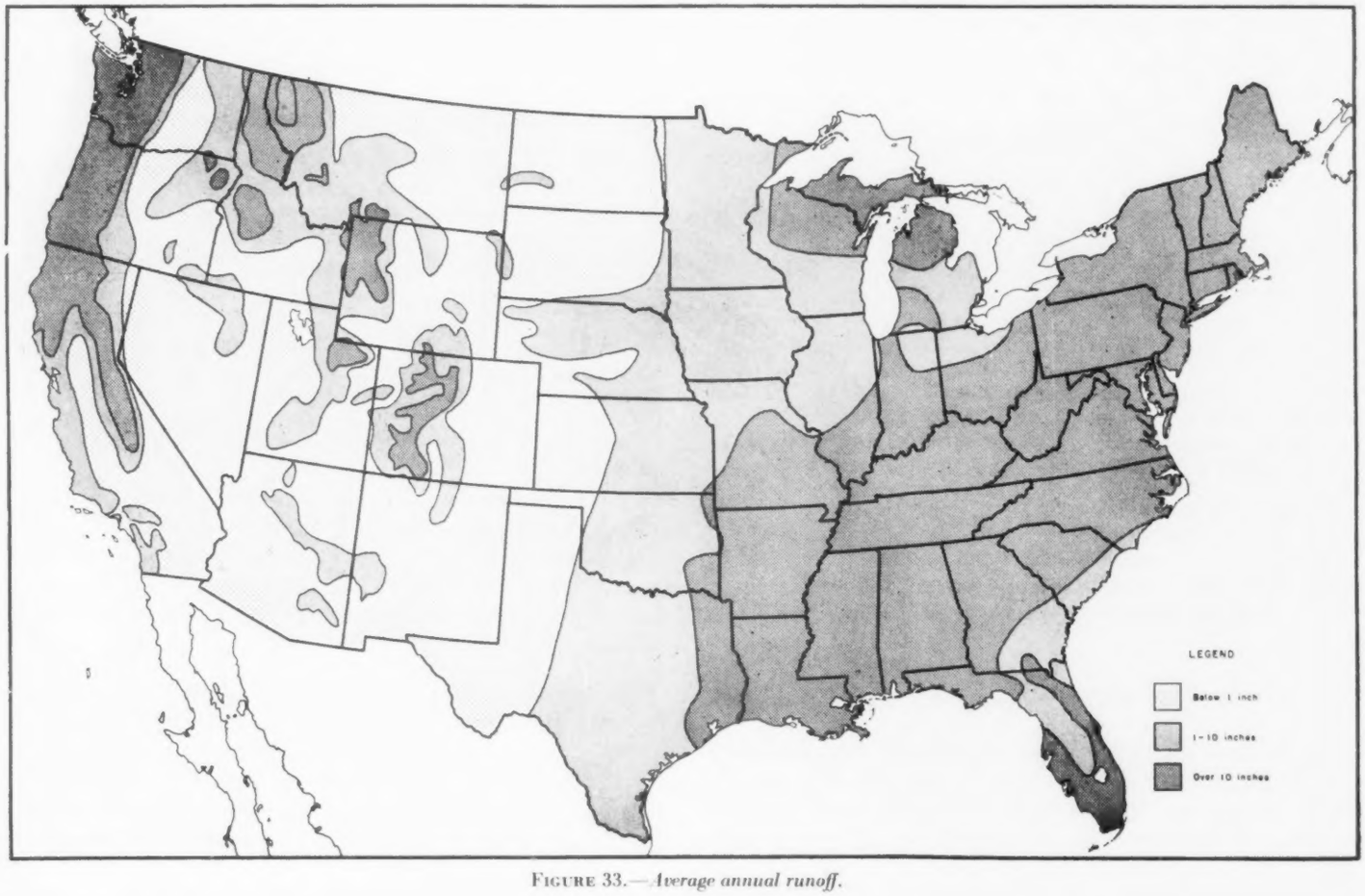

FIGURE 33.—*Average annual runoff.*

transpiration losses which have a prior assessment on the precipitation. Whether runoff is fairly uniform throughout the year or whether it consists mainly of the flow during one or two high-runoff periods is of vital importance to the economical use of water. Unfortunately, a satisfactory distribution seldom is approached in nature. Whereas the map showing the average annual runoff (fig. 33) represents the total result of day-to-day and month-to-month fluctuations in stream flow, the fact of the matter is that fluctuations follow the vagaries of the weather plus certain influences of terrain.

The fluctuations in flow of some streams follow those of precipitation rather closely; in others, flow lags behind the precipitation by many weeks, months, or even years. Therefore, it remains for mankind to devise practical and economical means of controlling flows resulting from periods of excessive rain or melting snow. It is appreciated readily that such waters must be stored for beneficial use during subsequent periods of low flow. Within a given geographic area the seasons of low or high flow recur in a general pattern that can be predicted after it has been studied over a reasonable period.

In such studies the amount of runoff produced by each storm is highly variable and reflects, for a given basin, numerous details of volume and intensity of rainfall, temperature, soil moisture and ground-water storage, and amount and type of vegetative cover.

The Seasons Have Pronounced Effects on Runoff

Much of the wintertime precipitation in the humid East, for example, finds its way into the streams because wet or frozen ground reduces infiltration and because transpiration from vegetation as well as the evaporation rate are both low in cold weather. A storm during summer will nearly always produce less runoff than an equal storm during winter.

The winter snow pack in the high mountains of the West does not melt until late spring or early summer producing runoff on which the farmers in the arid valleys depend for irrigation during the growing season.

Effects of Geology and Topography

The occurrence of runoff is everywhere conditioned by the geology. In some places there are features that illustrate the over-all effect unusually well. The most sensitive characteristic of a given drainage basin is the timing of fluctuations in stream flow, i. e., the time within which the runoff from a storm is discharged from the basin. In some watersheds the soil mantle and underlying rocks have a large capacity for accepting and storing precipitation as ground water. This is released to the streams at a relatively steady rate. Stream flow here may be well sustained during fair-weather periods and even during periods of prolonged drought.

On the other hand, a watershed which has a shallow soil mantle over impermeable rocks will have sharply concentrated flood peaks followed by low flow or even no flow between storms.

One example of a permeable soil or mantle rock that absorbs rainfall easily and permits it to percolate to such depths that it is effectively insulated from evaporation and transpiration is found in the sand hills of Nebraska. On Long Island the effect is similar, except that much of the water there finds its way directly to the sea without replenishing stream flow.

An example of the opposite effect can be seen in certain mountain streams in southern California, where the land is low in absorptive qualities and rainfall is shed rapidly.

Another major effect of geology on runoff arises where there is a difference between the above-ground or visible divide in a given watershed and the phreatic or under-ground divide. Runoff is ordinarily computed in terms of inches of depth, based on the surface area enclosed by the topographic divide. However, where there are hidden sinks and springs in limestone or modifications of the drainage system stemming from underground lava terraces the flow may be so modified that the direction of flow of underground water bears no relation to the topography above. The movement of ground water in permeable lava may be controlled by buried prelava divides rather than by the present upper surface.

Water piracy in a limestone area may even be so extensive as to tap water originating in another surface drainage basin. Of course, in a regional sense, the limestone or lava does not necessarily affect the total volume of runoff but only its distribution as between one basin and another. Outstanding examples of such effects are to be found in Comal County, Tex., and in Missouri. The east-flowing streams in the Black Hills region of South Dakota lose a large volume of water in passing through the steep gorges leading from the intermontane valleys to the Great Plains beyond. The water disappears into caves and sinkholes in massive upturned limestone beds.

Effect of Size of Drainage Basin

Annual runoff as expressed in inches is not necessarily affected by the size of a drainage area but there are important indirect effects. The runoff from small areas tends to reflect more strongly the effects of details of geology or topography. Variations tend to be compensating in large basins and the runoff approaches that which is normal for the climate.

Runoff from the smaller streams draining the more humid parts of the high mountains in the West, particularly in the basin and range province, generally decreases after the streams leave the mountains, owing to percolation into the desert-floor sediments. Many of these streams are of the quick "flash flood" type, their flow consisting almost entirely of storm water. Some drain the higher snow fields, and the meltwater produces a more sustained flow.

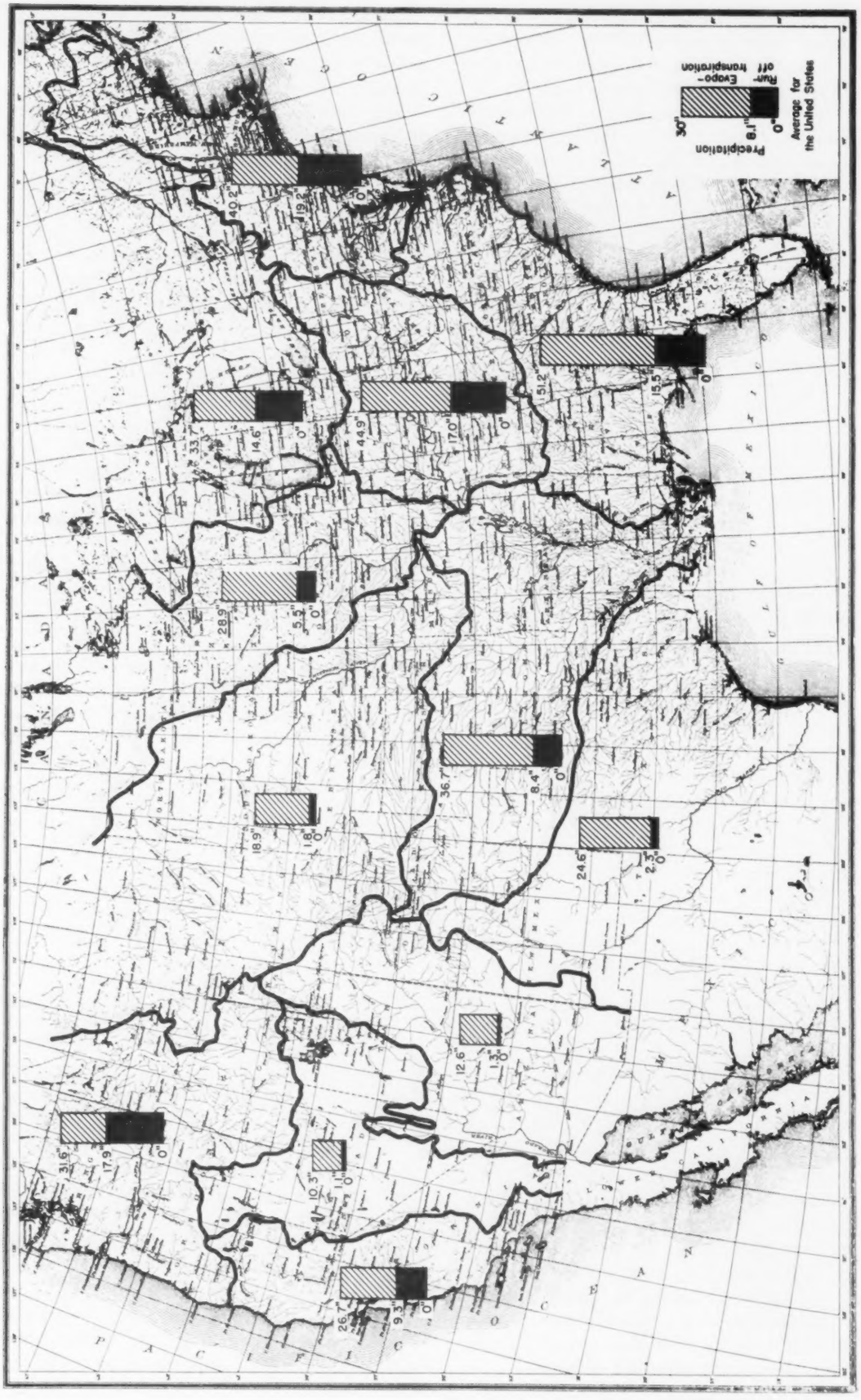

FIGURE 34.—*Precipitation, runoff, and evapotranspiration by major drainage basins.*

Effect of Vegetation

Vegetation ordinarily influences annual runoff through its effect on the processes of evaporation and transpiration. This includes the interception brought about by forest canopy, evaporation from the soil and from water surfaces, and transpiration by trees, shrubs, and ground cover.

Annual runoff represents the product of all natural climatic, geologic, and biologic factors. Some hydrologists argue that because annual runoff can be estimated dependably from consideration of climatic and geologic factors alone, vegetation needs no special consideration. This position, although confirmed by the experience of many engineering hydrologists, does not seem, from a scientific point of view, to be completely tenable. Problems of interdependence are present and require resolution. For example, one might argue with equal propriety that because it is possible to relate runoff to vegetation, soil, and geology, with residuals too small to be accounted for by climate, therefore the effect of climate should be considered inconsequential.

The literature on the relation of land use and vegetation to runoff is voluminous, and there seems to be no need to dwell on it in this short discussion beyond pointing out that where there is a definite limit to the amount of water available in a given basin and definite demands call for the major portion of such runoff for domestic or other local use, it would be wise to investigate the amount of water consumed by vegetation. Some plants, like willows and salt cedar, whose roots tap the shallow ground-water table under river-bottom lands, consume large quantities of water at the expense of stream flow and thus subtract from the total amount of water available at the basin outlet, thereby contributing to a shortage.

Water Storage

The industrial, urban, and to a large extent, the agricultural development of the United States depends on reservoir storage. The water supply of ancient Rome depended in part on reservoirs. In the arid and semiarid regions of the United States, where stream flow is largely derived from the runoff from melting snow, 75 percent or more of the total annual runoff flows out of each basin in the form of a huge wave, whose base may extend over several weeks, but whose crest is in general considerably in advance of the peak of irrigation demands. In humid areas, between 50 and 70 percent of the total annual runoff occurs in the form of intermittent stream rises or flood waves which result from the direct runoff from rains and melting snow. The other 30 to 50 percent is derived from ground water whose outflow is comparatively steady.

Without artificial storage, less than half of the runoff in the humid areas can be depended upon for regular use, and in arid and semiarid areas only a relatively small part of the total can be used beneficially. By storing the water contained in the peaks and flood rises, damaging floods can be avoided, and flow could be synchronized more closely with the demands for municipal water supply, irrigation, power, and navigation.

Beginning with power developments early in the history of New England, the development of reservoir storage now totals about 170,000,000 acre-feet (55,000,000 million gallons). The classification of this storage in relation to use is approximately as follows:

Use	Percent of total	Use	Percent of total
Power	39	Municipal use	6
Irrigation	22	Recreation	2
Flood control	19		
Navigation	12	Total	100

The aggregate capacity of these reservoirs is sufficient to contain 100 gallons per day for all the inhabitants of the United States during a period of 10 years. It is also equivalent to 13 percent of the total annual runoff from the United States.

The storage of water makes possible the utilization of water that otherwise would flow unused to the sea. However, water in surface reservoirs is subject to loss from evaporation and often from seepage. This is particularly significant in the arid and semiarid country. The loss by evaporation from reservoirs is estimated to total nearly 10,000,000 acre-feet per year. In nearly all cases the value of the storage is worth the toll exacted. But this picture may change as the capacity of efficient reservoirs is depleted by sediment.

Surplus waters for which storage reservoirs have not yet been built, and water now wasted by water-loving vegetation on river-bottom lands, may be the last major sources of water in many areas. No estimates are available of the ultimate storage capacity in the United States, but certainly several times the existing capacity will be needed to achieve complete control of the surface water supply.

Conclusions

Runoff is exceedingly variable. It varies in highly complex relationships with climate, geology, topography, and vegetative cover. Chances for increasing water supplies or making the present supplies secure depend in large part on understanding the factors that influence runoff.

It is important to know the amount of runoff because its regional value represents the total supply of water available for use. For the country as a whole, the total runoff (the discharge into the sea) of 1,800,000 cubic feet per second is far above the total water used. Only hydroelectric power generation, which is nonconsumptive and permits successive reuse of water, comes anywhere near this quantity. The records of runoff demonstrate that, through intelligent design, the streams can continue to be dependable sources of water supply. Water shortages that have occurred were caused mainly by overdevelopment resulting from unforeseen accelerated growth in population and requirements and, in some cases, by imprudent development resulting from inadequate basic data. The records of runoff also show that large additional supplies of water can be made available for development, through storage to carry water over from times of surplus to times of need, and by transportation from areas of excess to areas of deficiency.

Domestic and Industrial Uses of Water

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Introduction

THE DOMESTIC USE of water is universally classified as the most important beneficial use of that resource. Water is essential to life—the life of a city as well as the life of a human being. Without water, a man dies. Without water, a community faces the same fate.

In our appraisal of water uses in this country, the major domestic uses are included in that segment of uses usually referred to as municipal uses of water supply. This category also includes water for fire protection, street flushing, and other public uses, water for commercial establishments and a part of the water supply for industry.

Accelerating demands for water by cities are beginning to add up to a significant load on the water resources of the United States. In many parts of the country, the total use of water is reaching physical or economic limits. Evidence indicates that the use of water by municipalities tends to show a greater rate of increase than all other uses.

The American people have grown accustomed to the liberal use of water. More families than ever before in the United States have bathrooms and washing machines. New water-using devices, such as automatic dishwashing and garbage disposal fixtures, are appearing in the kitchen in increasing numbers. Air conditioning of factories, offices, and stores, with its added demand for water, is quite common.

The average per capita water use in 10 European cities, including London, Paris, Vienna, Edinburgh, and Berlin, before World War II was 39 gallons per day; while in the same number of American cities, it was 155 gallons per day. In the latter group are New York, Philadelphia, Baltimore, Chicago, and Detroit.

Trends in Domestic Use

In 1800, there were only 16 public water supply systems in the United States; by 1900, there were some 3,000; in 1948, there were more than 16,000 public water supplies providing almost two-thirds of this country's population their daily water requirements. The following table shows this phenomenal growth.

TABLE 8.—*Growth in number of United States water works*

Year	Number of works
1800 [1]	16
1810	26
1820	30
1830	44
1840	64
1850	83
1860	136
1870	243
1880	598
1890	1,878
1896	3,196
1924	9,850
1934 [2]	10,790
1939 [3]	12,760
1945	15,400
1948	16,700

[1] Data for 1800 to 1924, inclusive, from Manual of Water Works Practice. American Water Works Association.
[2] From Water Supply Practice.
[3] From Engineering News-Record.

Well over $6 billion is invested in the mains, treatment works, pumping stations, storage facilities, etc., that make water service possible.

The first United States public water supply system of which authentic record has been found is that of "The Water Works Co." of Boston, which in 1652 provided a supply for domestic consumption and fire protection to the residents of Boston's Conduit Street. Although limited to a single "neighborhood" within the city, this system was "public" in both purpose and performance, and as such must be considered the prime progenitor of all American public water works.

Not until almost a century later did the first supply designed to serve an entire community come into being. Then it was that a farmer named Schaeffer piped a supply from a spring on his farm down the main street of the Pennsylvania village now named Schaefferstown in his honor. The exact date of the project is obscure, but it is recorded that the system was operating in 1750 and that it was taken over by the municipality in 1763.

Meanwhile, at Bethlehem, Pa., in 1754, immigrant millwright Hans Christiansen, with the assistance of a visiting

West India missionary, John Boehner, began work on the first pumped public water supply works, placing the works in regular operation in 1755 and completing the project in 1761. And some years later, in 1774, Moravian brethren who had headed south from Bethlehem to found Salem (now Winston-Salem), N. C., began work on a gravity system and piped in their first supply in March 1776.

Other early systems, more or less complete in their service, were those of Geneva, N. Y. (1787), Portsmouth, N. H. (1798), and Morristown, N. J. (1799). And the supply provided at Winchester, Va., in 1799, appears to have been the first complete works developed as a public enterprise.

Immediately following the turn of the century, supplies were introduced in such prominent cities as Philadelphia, Newark, and Haverhill, Mass., and shortly thereafter at Baltimore and Wilmington; but, on the whole, activity in constructing works accelerated but slowly, so that by the end of 1850 only 72 public water supply systems could be counted. The decades which followed, however, evidenced remarkable progress—the first three adding 61, 92, and 366 systems, respectively, and the last two going well over a thousand each. And since the beginning of the twentieth century, of course, construction has proceeded at a rate too rapid to detail.

Practically all of the early supply works consisted of a short pipeline bringing water from a nearby spring or stream by gravity; generally there was no storage other than that provided by the intake or diversion works. The bored wood or lead pipe employed was of such limited capacity as to supply only the most meager domestic needs of the consumers, provision for fire protection being almost entirely absent. It was the later introduction of cast-iron pipe, first imported from England, which made possible larger-diameter lines capable of carrying the tremendous volumes of water actually required.

Before the middle of the nineteenth century, masonry aqueducts were laid on the hydraulic grade line from New York's Croton and Boston's Cochituate impounded surface supplies. Other cities used wood-stave wrought-iron-banded pipe, cement-mortar-lined pipe, or riveted wrought-iron pressure lines which were coated in the trench.

During the first two centuries of American waterworks history, the reciprocating steam pump was developed from its crude inefficient early stages to the familiar high-duty, cross-compound horizontal pumps and huge vertical triple-expansion pumps. Many of these highly efficient machines are giving as good service today as was demonstrated by their initial operation tests. The centrifugal pump, about a tenth the size and weight of the reciprocating pump of equal capacity, entered into competition first as a low-lift device. It has been so perfected during the last half century that it can be furnished to meet any head-capacity requirement and give dependable high-duty service. Thus, the centrifugal pump, with steam-turbine or electric-motor drive and often with internal-combustion-engine stand-by drive, is now almost universally used for water-pumping installations.

In 1870, when there were fewer than 250 waterworks in the country, Poughkeepsie, N. Y., built the first slow sand filter plant, designed in accordance with English practice. Failure to consider the difference in climate made the Poughkeepsie plant difficult to operate during the freezing winter months, but this situation was corrected a few years later by the provision of concrete groined arch covers, and the filters are still in operation. Less than 20 years after this introduction of filtration into America, the earliest mechanical, or rapid sand, filters were installed, and by the end of the century there were 10 times as many of these American type filters in service as there were of the English, slow sand type. A 1925 census revealed that this trend persisted, reporting in service 587 rapid sand and 47 slow sand filters, with a combined total rated capacity of about 5 billion gallons per day.

Not only filtration, but other types of water treatment have also shown great expansion, so that by 1940 treatment plants of all kinds numbered 5,372, producing more than 7 billion gallons of safe water per day. Chlorine treatment, first used in 1908, was by 1940 practiced in 4,590 systems, softening in 547, and iron or manganese removal in 598.

Today, in American cities, an average of less than 1 person in 100,000 per year dies of typhoid fever. This is a gratifying contrast to the nearly 100 deaths per year per 100,000 population at the turn of the century. Almost two-thirds of the Nation's population is now served by public waterworks systems through more than 20 million customer accounts averaging 4¼ persons per account, and it is this substantial service, involving well-supervised production and distribution of safe water supplies, which must be largely credited for wiping out the typhoid fever scourge of 50 years ago.

Yet, this remains a story of "progress" rather than "accomplishment," for today, as at any date in the past, the industry continues to exert its maximum effort toward attainment of ever higher goals of service and safety.

Cost of Urban Water

Administration of waterworks in most cities is an integral part of city government, and some systems pay their revenues into the general fund and operate on annual appropriations. Although this condition is generally confined to the smaller communities, it still exists in such large cities as New York and Philadelphia. A growing number of cities provide for the operation of their waterworks as public utilities under appointive boards and with funds kept separate from the general funds. Such is the situation in the Los Angeles Department of Water and Power. By recent authority to issue revenue bonds for construction, many such communities may construct needed additions to plant facilities without relation to limitation upon issuance of bonds secured by the real property of the community. Utility operation, under this plan, tends toward better management and sounder financing of the waterworks.

The historic cost of waterworks averages about $60 a person, but in cities importing their water great distances the cost may be twice as much. Costs have increased in recent years so that the present average for new construction is probably $100 to $125 for each person served in cities having nearby water supplies.

In spite of these increasing costs, water is one of the least expensive essential commodities that the public buys. Annual domestic water charges in the United States average only $6 a person, or less than 2 cents a day. In general, domestic water is procured, filtered, pumped, and distributed at the small cost of less than 5 cents a ton.

On the basis of such low costs there should be no American community that cannot afford an adequate domestic water supply. These figures also indicate that water can be sold at prices which should enable any domestic and industrial water supply features of multiple-purpose projects to be completely self-liquidating through payments by the communities benefited.

A major function of waterworks is to provide adequate quantities of water at adequate rates of flow for fire protection. While the capital cost of providing for fire protection may represent 25 to 40 percent of the cost of the waterworks, the quantity of water used annually for fire purposes is relatively small. In larger systems, it is an insignificant part of total annual requirements.

Increasing Requirements

The per capita use of water distributed by waterworks is slowly increasing. By 1945, the Public Health Service reported an average in the United States of 127 gallons per capita a day, varying from 60 gallons in communities of 500 population to 140 or 150 gallons in cities of 10,000 and over. Growing commercial and industrial activity, lawn sprinkling and semiagricultural uses, air conditioning, and generally higher standards of living and cleanliness explain, in large part, the increase in use.

Higher-than-average per capita use, taken alone, is not always proof of wasteful use or excessive leakage. Some cities use as much as 300 to 500 gallons per capita a day without waste, due to special conditions such as large estates or greater manufacturing activity. Use in unmetered cities may be much greater, due to waste and inadequate controls. In general, waterworks which account for more than 90 percent of production through metered sales to consumers reflect good construction and efficient operation.

Contamination and Purification

All natural waters contain some mineral and organic matter in suspension or in solution. While it is true that water-purification processes are available to treat most natural waters and make them safe and satisfactory for domestic and industrial use, the cost of such treatment may become burdensome.

Waterworks operators, therefore, are interested in all of the factors of watershed protection, land management, storage river maintenance, and best practical pollution control of both surface and ground water. Communities and industries which treat water before using it pour their wastes into streams, adding to the problems of other water users downstream. When these phases of contamination are better understood by our people, we may look forward to closer community cooperation in their elimination.

If clean rivers are maintained as proper habitats for fish and wildlife and for recreational use, then, in most cases, the water may readily be treated for domestic and industrial purposes. It should be pointed out, however, that a uniform and stable water quality is much to be desired. When flood control and other storages are built on rivers and streams, they do not always aid in protection of water quality. In fact, such reservoirs may produce large quantities of objectionable algae, or alter river temperatures. Also, outlets are often at great depth, which may make the dissolved oxygen content of the released water so low as to damage fish and wildlife and make the water generally objectionable for long distances downstream. The elevation of rivers and streams may be seriously affected, thereby putting all diverters of water to unnecessary additional expense.

The United States Public Health Service, through its quality requirements for drinking water supplied by public carriers in interstate commerce, has established standards of water quality. These standards have been accepted and adopted for the most part by all State boards of health, and all water works are required to comply with them. (Table 9.)

Industrial Uses of Water

To be realistic, a discussion of the industrial utilization of water might well start with the query "What does industry itself feel about the importance of water?"

One answer is to be found in the joint survey of water use in industry by the National Association of Manufacturers and the Conservation Foundation in their December 1950 report. (2) "Water," industry says, "is one of the essential raw materials for America's all important industrial plant. * * * A shortage of water for industrial purposes—just as surely as a shortage of manpower or of raw material or of capital—could defeat our purpose for future peace and prosperity and even imperil our national safety. No industry or business can long survive where water is unavailable or inadequate as to quantity and quality."

A major resource problem is the relationship of water to the present and future development of industry and the economic growth of the Nation.

Industrial Trends

The vision of an industrialized nation was in the minds of the fathers of our country. The trend to industrialization proceeded immediately upon the successful conclusion of the

TABLE 9.—*Basic water-use doctrines and State water-control agencies*

State	Basic law		State authorities								Interstate activities*	Notes
	Surface water	Ground water	Surface water	Ground water	Dams, diversion works, etc.	Quality and treatment—public supplies	Quality and treatment—industrial drinking water	Stream pollution control	Sewage disposal—technical	Industrial wastes—technical		
1. Alabama	Riparian doctrine.	Common law.	None	None	Secretary of State; Public Service Commission.[1]	Department of Public Health.	Department of Public Health.	Water Improvement Advisory Commission.	Water Improvement Advisory Commission; Department of Public Health.	Water Improvement Advisory Commission; Department of Public Health.	None	[1] Power and industrial use only.
2. Arkansas	Riparian doctrine.	Common law.	Resources and Development Commission (advisory).[1]	Resources and Development Commission (advisory).	Game and Fish Commission (fishways).	Board of Health.	Board of Health.	Water Pollution Control Commission in Board of Health.	Water Pollution Control Commission in Board of Health.	Water Pollution Control Commission in Board of Health.[2]	None	[1] Game and Fish Commission prevents lowering of stage of river which might affect fish life. [2] Oil and Gas Commission regulates disposal of wastes in subsurface formations.
3. Connecticut	Riparian doctrine.	Common law.	Department of Health.[1]	None	Board of Supervision of Dams.	Department of Health.	Department of Health.	Water Commission.	Department of Health.	Department of Health.	1, 3	[1] Advises General Assembly in granting charters.
4. Delaware	Riparian doctrine.	Common law.	None	None	None	Board of Health.	Board of Health.	Water Pollution Commission.[1]	Water Pollution Commission.[1]	Water Pollution Commission.[1]	2	[1] Board of Health is administrative agent.
5. Florida	Riparian doctrine.	Common law.	Trustees of Internal Improvement Fund;[1] Board of Conservation.	Board of Conservation.[1]	Board of Conservation.[1]	Board of Health.	Board of Health.	Board of Health.	Board of Health.	Board of Health.	None	[1] Division of Water Survey and Research is advisory agency.
6. Georgia	Riparian doctrine.	Common law.	None	None.[1]	Game and Fish Commission (fishways).	Department of Public Health.	Department of Public Health.	None.[1]	Department of Pubic Health.	Department of Public Health.	None	[1] Local control in some areas. [2] Riparian doctrine only.
7. Illinois	Riparian doctrine.	Common law.	None.[1]	Department of Mines and Minerals (submission of well logs).[2]	Department of Public Works and Buildings.	Department of Public Health.	Department of Public Health (only when part of public supply).	Sanitary Water Board.	Sanitary Water Board.	Sanitary Water Board.	5, 16, 17.	[1] Water Resources and Flood Control Board is coordinating agency. [2] Water Survey Division provides research and technical services.
8. Indiana	Riparian doctrine.	Common law.[1]	None	Department of Conservation.	Flood Control and Water Resources Commission.	Board of Health.	Board of Health.	Stream Pollution Control Board.[2]	Board of Health.	Board of Health.	5, 16, 17.	[1] With some restrictions on use. [2] Technical assistance by Board of Health.
9. Iowa	Riparian doctrine.	Common law.	Natural Resources Council.	Natural Resources Council.	Natural Resources Council.	Department of Health.	Bureau of Labor.[1]	Department of Health; Conservation Commission.	Department of Health.	Department of Health.	17, 18	[1] Department of Health advises on industrial hygiene.
10. Kentucky	Riparian doctrine.	Common law.	Department of Conservation (advisory).	Department of Conservation (advisory).	None	Department of Health.	Department of Health.	Water Pollution Control Commission.[1]	Water Pollution Control Commission.[1]	Water Pollution Control Commission.[1]	5	[1] Effective June 17 1950; technical assistance furnished by Department of Health and other State agencies.

*The numerals in this column indicate membership in the correspondingly numbered interstate compacts, agreements, and agencies following table 9.

TABLE 9.—*Basic water-use doctrines and State water-control agencies*—Continued

State	Basic law		State authorities								Interstate activities*	Notes
	Surface water	Ground water	Surface water	Ground water	Dams, diversion works, etc.	Quality and treatment—public supplies	Quality and treatment—industrial drinking water	Stream pollution control	Sewage disposal—technical	Industrial wastes—technical		
11. Louisiana	Riparian doctrine.[1]	Common law.[1]	None	None	Department of Public Works; Department of Wildlife and Fisheries.	Department of Health.	Department of Health.	Stream Control Commission.[2]	Department of Health.	Stream Control Commission; Department of Health.	None	[1] These concepts provided for in civil code. [2] Administrative agency is Department of Wildlife and Fisheries.
12. Maine	Riparian doctrine.	Common law	Water Resources Division of Public Utilities Commission.	None	Public Utilities Commission	Department of Health and Welfare.	Department of Health and Welfare.	Sanitary Water Board.[1]	Department of Health and Welfare.	Sanitary Water Board.	None	[1] Department of Health and Welfare and Public Utilities Commission have concurrent jurisdiction over certain phases.
13. Maryland	Riparian doctrine.[1]	Common law.[1]	Department of Geology, Mines, and Water Resources (except municipal supplies).	Department of Geology, Mines, and Water Resources (except municipal supplies).	Department of Geology, Mines, and Water Resources (except municipal supplies).	Board of Health	Board of Health.	Water Pollution Control Commission.	Water Pollution Control Commission; Board of Health.	Water Pollution Control Commission; Board of Health.	4	[1] Diversion of waters for purposes other than municipal, domestic, or farm use controlled by Department of Geology, Mines, and Water Resources
14. Massachusetts	Riparian doctrine.[1]	Common law.	County Commissioners.	None	County Commissioners.	Department of Public Health.	Department of Public Health.	Department of Public Health; Department of Conservation (protection of aquatic life).	Department of Public Health.	Department of Public Health.[2]	3	[1] Legislature has enacted laws controlling specific supplies. [2] Department of Public Safety has power over discharge of oil into its waterways.
15. Michigan	Riparian doctrine.	Common law.	Water Resources Commission.	Water Resources Commission; Department of Conservation (advisory).	County boards of supervisors.	Department of Health.	Department of Health.	Water Resources Commission.	Department of Health.[1]	Department of Health.[1]	16	[1] Notice of any new disposal of waste must be given to Water Resources Commission, which sets minimum restrictions on treatment.
16. Minnesota	Appropriation doctrine.[1]	Appropriation doctrine.[1]	Department of Conservation.	Department of Conservation.	Department of Conservation.	Department of Health.	Department of Health.	Water Pollution Control Commission.[2]	Water Pollution Control Commission.[2]	Water Pollution Control Commission.[2]	6, 16–19	[1] Does not apply to beneficial uses and rights in existence on July 1, 1937, nor to use for any purpose originating within a municipality or for less than 25 persons. [2] Department of Health is administrative and technical agency.
17. Mississippi	Riparian doctrine.	Common law.	None	None	None	Board of Health.	Board of Health	Fish and Game Commission	Board of Health.	Fish and Game Commission.	None	

18. Missouri	Riparian doctrine.	Common law.	Division of Geological Survey and Water Resources (advisory)[1].	Division of Geological Survey and Water Resources (advisory)[1].	Conservation Commission (fishways).	Division of Health of Department of Public Health and Welfare.	Division of Health of Department of Public Health and Welfare.	Division of Health (health aspects); Conservation Commission (fish life).	Division of Health.	Division of Health.	17, 18	[1] Division of Research and development also advisory.
19. New Hampshire	Riparian doctrine.	Common law.	Water Resources Board; legislative charters.	None	Water Resources Board.	Department of Health.	Department of Health.	Water Pollution Committee.[1]	Water Pollution Committee.[1]	Water Pollution Committee.[1]	None	[1] Department of Health is administrative agency.
20. New Jersey	Riparian doctrine.[1]	Common law.[2]	Division of Water Policy and Supply of Department of Conservation and Economic Development.	Division of Water Policy and Supply of Department of Conservation and Economic Development.	Division of Water Policy and Supply of Department of Conservation and Economic Development.	Department of Health.	Department of Health.	Department of Health.	Department of Health.	Department of Health.	1, 2	[1] Except that State controls municipal water supplies. [2] In certain areas, State controls withdrawals in excess of 100,000 gallons per day.
21. New York	Riparian doctrine.	Common law and reasonable use rule.[1]	Water Power and Control Committee.	Water Power and Control Committee.[1]	Department of Public Works.	Department of Health (except New York City).	Department of Health (except New York City).	Water Pollution Control Board.[2]	Water Pollution Control Board; Departments of Health and Conservation (up to 1960).	Water Pollution Control Board; Departments of Health and Conservation (up to 1960).	1-3, 5, 16.	[1] Controls apply only to public supplies, except on Long Island, where all supplies are controlled. [2] New York City has jurisdiction over its watersheds.
22. North Carolina.	Riparian doctrine.	Reasonable use rule.	Department of Conservation and Development (advisory).	None	Advisory Committee on Hydroelectric Development and Flood Control (advisory).	Board of Health.	Board of Health.[1]	No pollution control law.[2]	Board of Health.	Board of Health (advisory); Stream Sanitation Committee (advisory).	None	[1] Only where supply serves more than 10 residential users. [2] Stream Sanitation Committee authorized to make study of pollution.
23. Ohio	Riparian doctrine.	Common law.	Division of Water of Department of Natural Resources.[1]	Division of Water of Department of Natural Resources.[1]	Division of Water of Department of Natural Resources (for industrial supplies	Department of Health.	Department of Health.	Department of Health.	Department of Health.	Department of Health.	5, 16	[1] Fact-finding and research only.
24. Pennsylvania	Riparian doctrine.	Common law.	Water and Power Resources Board (public water supplies only).	None	Water and Power Resources Board.	Department of Health.	Department of Health.	Sanitary Water Board in Department of Health.	Sanitary Water Board in Department of Health.	Sanitary Water Board in Department of Health.	2, 4, 5, 16.	
25. Rhode Island	Riparian doctrine.	Common law.	None	None	Division of Rivers and Harbors of Department of Public Works.	Department of Health.	Department of Health (advisory.)[1]	Department of Health.	Department of Health.	Department of Health.	3	[1] Department of Health inspects such supplies; Department of Labor has legal authority to require safe drinking water.
26. South Carolina	Riparian doctrine.	Common law.	None	None	Board of Health; Game and Fish Department (fishways).	Board of Health.	Board of Health.	None.[1]	Board of Health.	Board of Health.	None	[1] No stream-pollution-control law other than for prevention of discharge of wastes prejudicial to public water supplies.

*The numerals in this column indicate membership in the correspondingly numbered interstate compacts, agreements, and agencies, following table 9.

TABLE 9.—*Basic water-use doctrines and State water-control agencies*—Continued

State	Basic law		State authorities								Interstate activities*	Notes
	Surface water	Ground water	Surface water	Ground water	Dams, diversion works, etc.	Quality and treatment—public supplies	Quality and treatment—industrial drinking water	Stream pollution control	Sewage disposal—technical	Industrial wastes—technical		
27. Tennessee	Riparian doctrine.	Common law.	None	None	Circuit court of county;[1] Department of Public Health.	Department of Public Health.	Department of Public Health.	Stream Pollution Control Board.[2]	Stream Pollution Control Board.[2 3]	Stream Pollution Control Board.[2]	None	[1] Also Tennessee Valley Authority. [2] Department of Public Health gives technical aid. [3] Power to issue orders on sewage disposal curtailed until 1951.
28. Vermont	Riparian doctrine.	Common law	Commission of Water Resources (advisory).	None	Water Conservation Board.	Board of Public Health.	Board of Public Health.	Water Conservation Board.	Water Conservation Board.	Water Conservation Board.	None	
29. Virginia	Riparian doctrine.	Common law.	None	Geological Survey (to be notified).	Circuit courts; Corporation Commission (Hydroelectric power).	Department of Health.	Department of Health.	Water Control Board.	Department of Health.[1]	Water Control Board.	4, 5.	[1] Water Control Board issues certificate after approval by Department of Health.
30. West Virginia	Riparian doctrine.	Common law.	None	None	Public Service Commission.	Health Department.	Health Department.	Water Commission.	Health Department.	Health Department; Water Commission.	4, 5.[1]	[1] Participation in this commission ruled unconstitutional by State supreme court, April 4, 1950.
31. Wisconsin	Riparian doctrine.	Common law.[1]	Public Service Commission.	Board of Health.[1]	Public Service Commission.	Board of Health.	Board of Health.	Committee on Water Pollution, with Board of Health.[2]	Board of Health.	Committee on Water Pollution with, Board of Health.[2]	16, 17.	[1] Board of Health controls use of ground water to prevent impairment of public utility wells. [2] Board of Health serves as administrative agency.
32. Arizona	Appropriation doctrine.	Reasonable use rule.[1]	State Water Commissioner; Water Division, State Land Department.	State Water Commissioner; Water Division, State Land Department.	State Water Commissioner; Water Division, State Land Department.[2]	Department of Health.	Department of Health.	Department of Health.[3]	Department of Health.[3]	Department of Health.[3]	14, 15.	[1] Appropriation doctrine for subsurface streams. [2] Dams more than 10 ft. high or 50-acre-ft. capacity. [3] Game and Fish Commission can file suit to prevent pollution that would injure fish or wildlife.
33. California	Riparian and appropriation doctrines.[1]	Reasonable use rule.	Division of Water Resources of Department of Public Works.	Division of Water Resources of Department of Public Works.	Division of Water Resources of Department of Public Works.	Department of Public Health.	None	Water Pollution Control Board; Department of Public Health (public health hazards only).	Water Pollution Control Board; Department of Public Health (public health hazards only).	Water Pollution Control Board; Department of Public Health (public health hazards only).	15.	[1] Riparian right is superior to appropriation right, except that riparian right shall not extend to unreasonable use; other conditions may also subordinate riparian right.

34. Colorado	Appropriation doctrine.	Appropriation doctrine.	State Engineer; Water Conservation Board (advisory).	State Engineer; Water Conservation Board (advisory).	State Engineer; Water Conservation Board (advisory).	Department of Public Health.	Department of Public Health.	Department of Public Health.	Department of Public Health.	Department of Public Health.	8–10, 12–15, 18.	
35. Idaho	Appropriation doctrine.	Appropriation doctrine.	Department of Reclamation.	Department of Reclamation.	Department of Reclamation.[1]	Department of Public Health.	Department of Public Health.	Department of Public Health (advisory).[2]	Department of Public Health (advisory).[2]	Department of Public Health (advisory).[2]	None	[1] For dams more than 10 feet high or 100 acre-feet capacity. [2] No antipollution law.
36. Kansas	Appropriation doctrine.	Appropriation doctrine.	Chief Engineer, Division of Water Resources of Board of Agriculture.	Chief Engineer, Division of Water Resources of Board of Agriculture.	Chief Engineer, Division of Water Resources of Board of Agriculture.	Board of Health.	None	Board of Health.	Board of Health.	Board of Health.	8, 10, 18.	
37. Montana	Appropriation doctrine.	Common law [1]	State Engineer; Water Conservation Board.	State Engineer; Water Conservation Board.	Board of County Commissioners.[2]	Board of Health.	Board of Health.	Board of Health.	Board of Health.	Board of Health.	18	[1] Except for ground waters flowing in defined underground streams. [2] Acts only upon complaint that dam is insecurely built.
38. Nebraska	Appropriation doctrine. [1]	Appropriation doctrine; reasonable use rule.	Department of Roads and Irrigation.	Department of Roads and Irrigation.	Department of Roads and Irrigation.	Department of Health.	Department of Health.	Department of Health.[2]	Department of Health.[2]	Department of Health.[2]	9, 10, 18.	[1] Riparian and common law doctrines apply for lands privately owned prior to 1889. [2] Game, Forestation and Parks Commission has authority where aquatic life is affected.
39. Nevada	Appropriation doctrine.	Appropriation doctrine.[1]	State Engineer.	State Engineer.	State Engineer.	Department of Health.	Department of Health.	Department of Health.	Department of Health.	Department of Health.[2]	15	[1] Does not apply to domestic use from non-artesian ground water sources. [2] Mining industry exempted as to tailings.
40. New Mexico	Appropriation doctrine.	Appropriation doctrine.	State Engineer.	State Engineer.	State Engineer.	Board of Health.	Board of Health.	Board of Health.	Board of Health.	Board of Health.	11–15.	
41. North Dakota	Riparian and appropriation doctrines.	Appropriation doctrine.[1]	State Engineer; Water Conservation Commission.	State Geologist.	Water Conservation Commission.[2]	Department of Health.	Department of Health.	Department of Health; Water Conservation Commission.[3]	Water conservation Commission; Department of Health.	Water conservation Commission; Department of Health.	6, 19	[1] Applies only to subsurface streams. [2] Dams higher than 10 feet or more than 30 acre-feet capacity. [3] Game and Fish Department exercises control where fish are affected.
42. Oklahoma	Riparian and appropriation doctrines.	Reasonable use rule.	Planning and Resources Board.	Planning and Resources Board.	Planning and Resources Board.[1]	Department of Health.	Department of Health.	Department of Health.	Department of Health.	Department of Health.	None	[1] In addition, Department of Health must approve plans of dams or diversion works used for domestic water supply.

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TABLE 9.—*Basic water-use doctrines and State water-control agencies*—Continued

State	Basic law		State authorities								Interstate activities*	Notes
	Surface water	Ground water	Surface water	Ground water	Dams, diversion works, etc.	Quality and treatment—public supplies	Quality and treatment—industrial drinking water	Stream pollution control	Sewage disposal—technical	Industrial wastes—technical		
43. Oregon	Appropriation doctrine.	Appropriation doctrine.[1]	State Engineer; Hydroelectric Commission (power).	State Engineer	State Engineer[2]; Hydroelectric Commission (power); Fish and Game Commission (fishways).	Board of Health	Board of Health.[3]	Sanitary Authority in Board of Health.	Sanitary Authority in Board of Health.	Sanitary Authority in Board of Health.	None	[1] East of summit of Cascade Mountains. [2] Except dams lower than 10 feet or less than 3-million-gallon capacity. [3] Only for more than 50 persons.
44. South Dakota	Riparian and appropriation doctrines.[1]	Beneficial use rule and appropriation doctrine.[2]	State Engineer; Natural Resources Commission.	State Engineer; Natural Resources Commission.	State Engineer	Board of Health.	Board of Health.	Water Pollution Committee.	Water Pollution Committee.	Water Pollution Committee.	6, 7, 18, 19.	[1] Navigable waters may not be appropriated. [2] Subsurface waters not forming definite stream (except artesian waters) subject to common law.
45. Texas	Appropriation doctrine.[1]	Common law[2].	Board of Water Engineers.	Board of Water Engineers.	Board of Water Engineers.	Department of Health.	Department of Health.	Department of Health.[3]	Department of Health.[3]	Department of Health.[3]	11, 12	[1] Riparian doctrine applies to lands privately owned prior to 1889. [2] Underflow of streams subject to appropriation. [3] Game, Fish and Oyster Commission authorized to control pollution affecting aquatic life.
46. Utah	Appropriation doctrine.	Appropriation doctrine.	State Engineer[1].	State Engineer[1]	State Engineer[1].	Department of Health.	Department of Health.	No stream pollution control law.[2]			14, 15	[1] Water and Power Board advisory. [2] Health laws permit cities to maintain jurisdiction over watersheds.
47. Washington	Appropriation doctrine.	Reasonable use rule.	State Supervisor of Hydraulics.	State Supervisor of Hydraulics.	State Supervisor of Hydraulics.	Department of Health.	Department of Health.[1]	Pollution Control Commission.	Pollution Control Commission.	Pollution Control Commission.	None	[1] Smaller industrial supplies are under supervision of local health departments.
48. Wyoming	Appropriation doctrine.	Common law[1]	State Engineer[2]; Board of Control.	State Engineer[2]; Board of Control.	State Engineer[3]	Board of Health	Board of Health.	Board of Health.	Board of Health.	Board of Health.	7, 14, 15, 18.	[1] Except that underground streams may be subject to appropriation. [2] Planning and Water Conservation Board (advisory). [3] Dams above 5 feet across running streams and all dams above 10 feet.

* The numerals in this column indicate membership in the correspondingly numbered interstate compacts, agreements and agencies listed following table 9.

Interstate Commissions, Compacts and Agreements

CONGRESS-APPROVED COMMISSIONS AND COMPACTS

Name	Participating States
1. Tri-State Pollution Compact (Interstate Sanitation Commission).	Connecticut, New Jersey, New York.
2. Interstate Commission on the Delaware River Basin.	Delaware, New Jersey, New York, Pennsylvania.
3. New England Interstate Water Pollution Control Commission.	Connecticut, Massachusetts, New York, Rhode Island.
4. Interstate Commission on the Potomac River Basin.	District of Columbia, Maryland, Pennsylvania, Virginia, West Virginia.
5. Ohio River Valley Water Sanitation Commission.	Illinois, Indiana, Kentucky, New York, Ohio, Pennsylvania, Virginia, West Virginia.*
6. Red River Flood Control Compact (Tri-State Water Commission).	Minnesota, North Dakota, South Dakota.
7. Belle Fourche River Compact	South Dakota, Wyoming.
8. Arkansas River Compact	Colorado, Kansas.
9. South Platte River Compact	Colorado, Nebraska.
10. Republican River Compact	Colorado, Kansas, Nebraska.
11. Pecos River Compact	New Mexico, Texas.
12. Rio Grande Compact	Colorado, New Mexico, Texas.
13. Costilla Creek Compact and La Plata River Compact.	Colorado, New Mexico.
14. Upper Colorado River Basin Compact.	Arizona, Colorado, New Mexico, Utah, Wyoming.
15. Colorado River Compact	Arizona, California, Colorado, Nevada, New Mexico, Utah, Wyoming.

INFORMAL AGREEMENTS AND AGENCIES

16. Great Lakes Drainage Basin Sanitation Agreement.	Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, Wisconsin.
17. Upper Mississippi River Drainage Basin Sanitation Agreement.	Illinois, Indiana, Iowa, Minnesota, Missouri, Wisconsin.
18. Missouri River Basin Health Council	Colorado, Iowa, Kansas, Minnesota Missouri, Montana, Nebraska, South Dakota, Wyoming.
19. Red River Basin Sanitation Agreement (Interstate Sanitation Committee).	Minnesota, North Dakota, South Dakota.

*West Virginia's participation in this commission ruled unconstitutional by State supreme court, April 4, 1950.

Revolution. The first half of the nineteenth century saw the development of basic policies and legislation looking forward to the protection of our youthful industrial economy. Continuously through that century, industry grew until by the turn of the century (1900) the promise of American industrial might began to come true. Since 1900 the growth of American industry has been phenomenal. Chart I shows growth, as measured by Federal Reserve Board indices, from just over 25 to about 200, an over-all growth of 800 percent in 50 years (fig. 35).

In 1935 the might of American industry was world-renowned. Yet, by 1950 industries' productive capacity had more than doubled. The continuation of economic growth is shown by the fact that a 7-percent increase in total output occurred during 1950. The current productive plan, according to the Economic Report of the President, January 1951, (3) is "to increase the total productive strength of our economy by at least 25 percent in the next 5 years."

Specifically illustrating this trend is the history of the chemical process industry between 1910–50. Measured by output in billions of dollars, this industry has grown from 4 billion in 1910 to 40 billions in 1950 (4).

Amounts of Water Used

Major deficiencies exist in data concerning the volumes of water used by the Nation's industrial machine. The uses of water in industry are for processing, cooling, boiler feed, sanitary and service, and other purposes. According to *Water in Industry* (2) the approximate percentages used for these various purposes are as follows: process about one-third, cooling another third, 10 percent for boiler feed purposes, about 15 percent for sanitary and service use and the balance for other miscellaneous service. The report of the President's Water Resources Policy Commission (5) states the following concerning the total volumes of water required by industry in comparison to other major consumers of water:

> According to estimates by the Geological Survey the following water uses account for 14 percent of the Nation's yearly runoff to the oceans:[1]

TABLE 10.—*Nation's water use*

	Billions of gallons per day
Irrigation	75
Industrial	77
Municipal	14
Rural (other than irrigation)	3.6
Total	170

These figures represent gross withdrawals at sources; net consumptive use is very much less. Domestic use accounts for only about 1 percent of runoff of our rivers.

The estimate of 77 billion gallons per day by the United States Geological Survey for industrial uses includes water used for cooling purposes. It is seven times as high as the 10 billion gallons industry itself estimates it uses.

These high and low figures can be reconciled only on the basis that the Geological Survey figures include great quantities of cooling water

[1] Actual values have been adjusted to agree with the latest United States Geological Survey Estimate on Nation's Water Use in 1950, released April 30, 1951.

* The numerals in this column indicate membership in the correspondingly numbered interstate compacts, agreements and agencies listed following table 9.

which are returned to the river at higher temperature but essentially unchanged in quantity.

Powell and Bacon (6), table 11, have estimated the industrial use by major water industries for 1947.

Quality of Water Required for Industrial Uses

Water quantity by itself is not sufficient for today's highly complex industrial machine. The quality characteristics of water is a highly important factor. A limiting factor, and a problem which will grow more important unless accelerated prevention action is taken, is that imposed by the problem of water pollution.

The habit and practice of dumping into the surface waters of the United States the wastes, largely untreated or inadequately treated, by cities and factories, thereby adding solids, organic substances, toxic chemicals, acids and alkaline materials, increased temperature, color, turbidity, oil, and similar wastes, place a large economic cost against the Nation in terms of the treatment required to make waters available for utilization by industry (fig. 36).

The required quality of water for industrial use depends upon the specific use of the water. Many industries employ several qualities of water, individually treated to obtain the necessary properties for a specific purpose. Some industries have their own plants for their water supply purification while many are large consumers of municipal waters. Because industries purchase large volumes of water, industrial requirements are usually considered in the construction of municipal plants.(7) The standards of quality required for industry cover a wide range. At one end of the scale is water used for cooling purposes. The quality requirements for this water are low. At the other end of the scale is water used in the food industries. This water usually must conform with standards as strict and sometimes stricter than those of a domestic supply.

TABLE 11.—*Estimated industrial water use by major water-using industries, 1947*

Industry	Number of establishments	Value added by manufacture $1,000 units	Production		1947 water use (estimated)	
			Amount	Unit	Gallons per unit	Million gallons
Steel (finished)	419	2, 659, 250	61, 857, 241	Ton	65, 000	4, 020, 721
Oil refining	437	1, 494, 474	1, 887, 890, 000	Barrel	770	1, 452, 675
Gasoline		[1]	791, 325, 000	do	357	791, 325
Wood pulp:						
Sulfate		[1]	5, 356, 710	Ton	64, 000	342, 829
Sulfite		[1]	2, 795, 960	do	60, 000	167, 758
Soda		[1]	491, 580	do	85, 000	41, 784
Ground wood		[1]	2, 049, 814	do	5, 000	10, 249
Total	226	415, 938		Ton		562, 520
Paper		[1]	10, 646, 833	Ton	39, 000	415, 226
Paper board		[1]	9, 186, 810	do	15, 000	137, 802
Total	665	1, 050, 108	19, 833, 643	Ton		553, 028
Coke	167	[1]	79, 146, 000	do	3, 600	284, 493
Beer	440	808, 946	88, 027, 000	Barrel	470	41, 373
Whisky	226	472, 357	246, 443, 000	Gallon	80	21, 155
Milk, cream, and butter [2]		[1]	71, 440, 000, 000	Pound	0.11–0.25	14, 286
Canning and preserving [3]	2, 265	609, 939	391, 546, 000	Case	7.5–250	[4] 8, 520
Manufactured ice [5]	3, 423	226, 584	36, 100, 000	Ton	243.85	8, 802
Soft drinks	5, 618	421, 000	927, 700, 000	Case	2.5	6, 250
Woolens and worsted fabrics	495	599, 534	464, 563, 000	Pound	70	3, 252
Wool scouring	74	54, 166	210, 172, 000	do	1.26	2, 648
Tanning	561	403, 783	238, 731, 000	do	8	1, 910
Soap	249	450, 721	4, 138, 001, 000	do	0.25	1, 034
Meat packing (hogs)	2, 153	[1]	51, 678, 047	Hogshead	11	568
Cane sugar [6]	25	98, 112	358, 000	Ton	1, 000	358
Rayon (all types)	38	447, 900	746, 900, 000	Pound	0.16	119

[1] Value added by manufacture is not given on same basis as production and water consumption.
[2] Based on U. S. Department of Agriculture figures for creamery butter, liquid milk, and cream sold in communities. No other milk products subject to water consumption estimates.
[3] Excluding fish.
[4] Includes only water used in processing 14 fruits and vegetables for which consumption factors are available. This accounts for 177,321,000 cases. Total water used by this group is probably 2 or 3 times as high.
[5] Includes filling cans and pulling cores.
[6] Includes refining only.

Source: Sheppard T. Powell and Hilary E. Bacon, August 1950, Journal of the American Waterworks Association.

Both fresh and saline waters are used for cooling condensers. Two of the most important requirements are that the water should not be unduly corrosive and that it should not cause excessive deposition of scale.(8) If large amounts of organic material occur in cooling waters the efficiency of cooling is apt to be impaired and the growth of gelatinous masses of bacteria and fungus may cause unpleasant odors. The cost of treating such water is often higher. The requirements of water for boiler feed are more exacting. For boilers operating at low pressures water is frequently used without preliminary treatment; for higher pressures, where the composition of the water is more important, treatment such

INDEX OF RISING INDUSTRIAL PRODUCTION IN THE UNITED STATES (1935-39 average equals 100)

Source: 1919-49 Federal Reserve Board index of industrial production, 1950 estimated; 1899-1918 indexes compiled by National Bureau of Economic Research linked to Federal Reserve Board index on basis of year 1919

FIGURE 35.—*Growth of industry.*

as softening, demineralization, and deaeration are often necessary.

The composition of water used for paper-making is important. For high-grade papers some of the usual quality requirements are softness, low iron and manganese content, freedom from suspended matter, low quantity of carbon dioxide and relative freedom from organic matter and bacteria. In the manufacture of soft beverages, the taste and odor characteristics of the water, organic matter present, and alkalinity are important factors to consider. Further treatment of community waters is often necessary to secure the required quality.

Soft water is preferred to hard water in many industries. Hard waters are detrimental to some industries such as soap manufacturing, wool degreasing, some types of dyeing, textile bleaching, tanning, and laundering. For a large number of industries, it is important that the water used should be very low in iron content; some examples are the bleaching, tanning, and dyeing industries.

Treatment of Industrial Water Supplies

Considering the foregoing general quality requirements of industrial waters, some of the following methods may be used to produce a satisfactory supply. Sedimentation may be used for the removal of silt and coarse slime, followed by sand filters for the removal of finer suspended particles and flocculant materials. Tastes and odors may be removed by the use of such chemicals as chlorine, chloramine, activated carbon, potassium permanganate, and chlorine dioxide. Aeration, coagulation, and filtration, and bleaching clays may also be used to remove odors and tastes from waters.

Chlorine, because of its powerful disinfection power, is

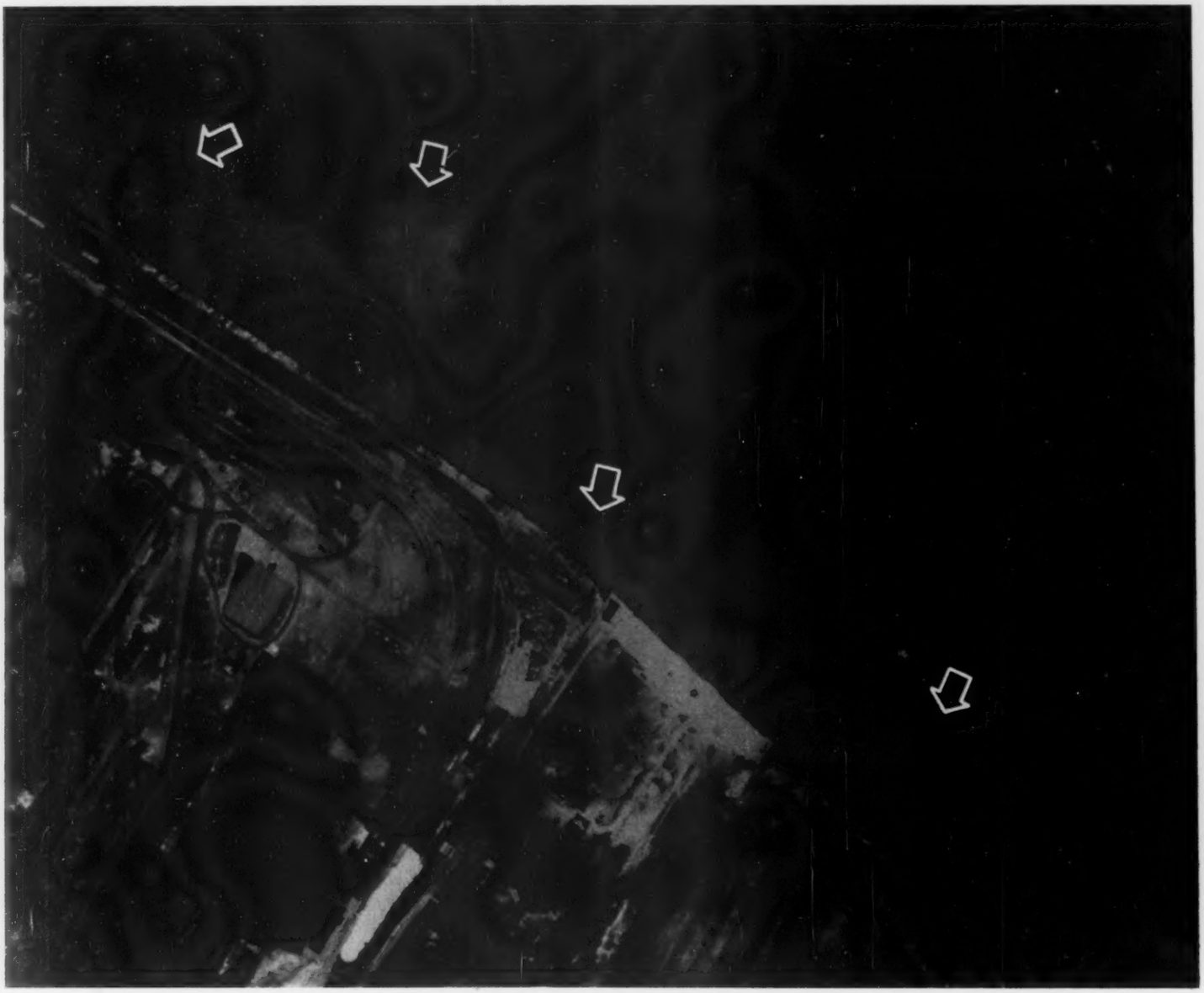

FIGURE 36.—*Water pollution.*

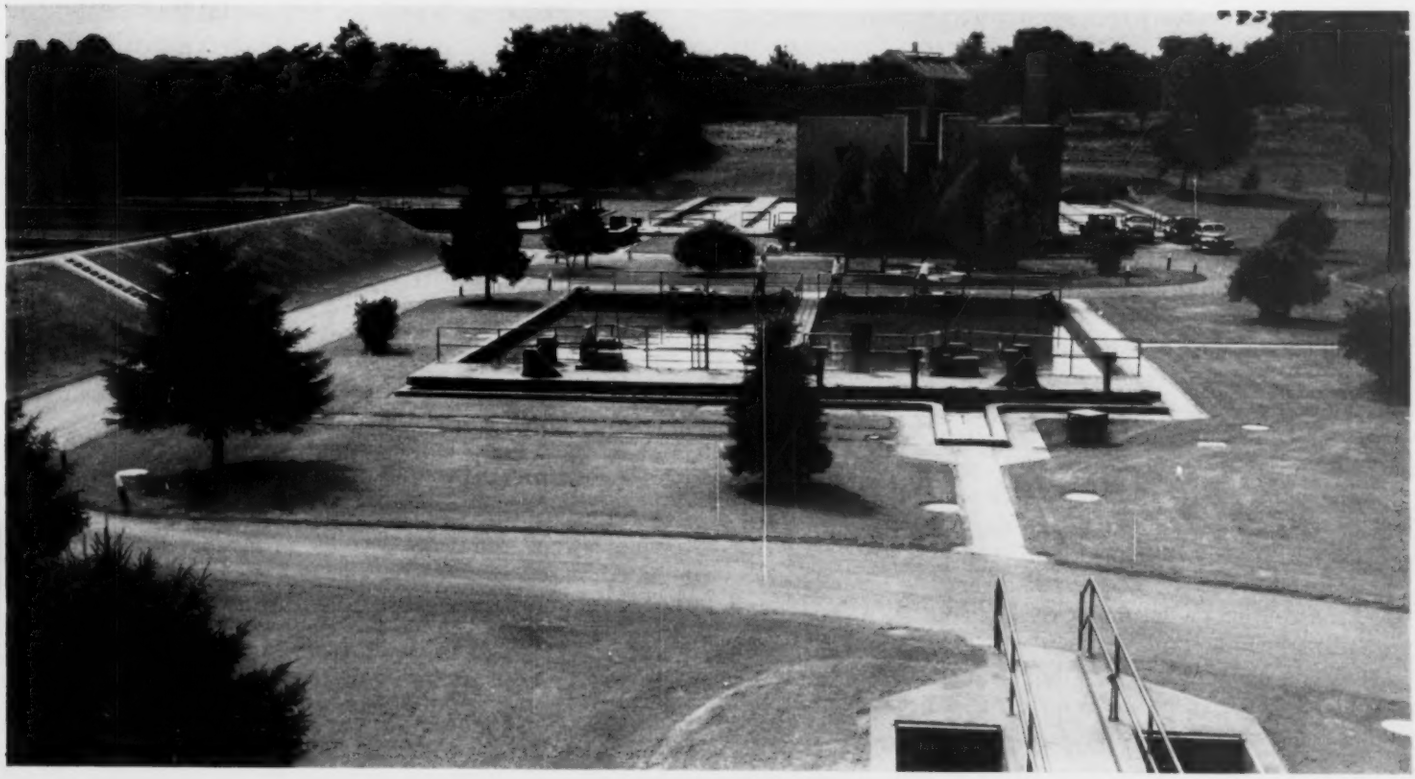

FIGURE 37.—*Municipal treatment plant.*

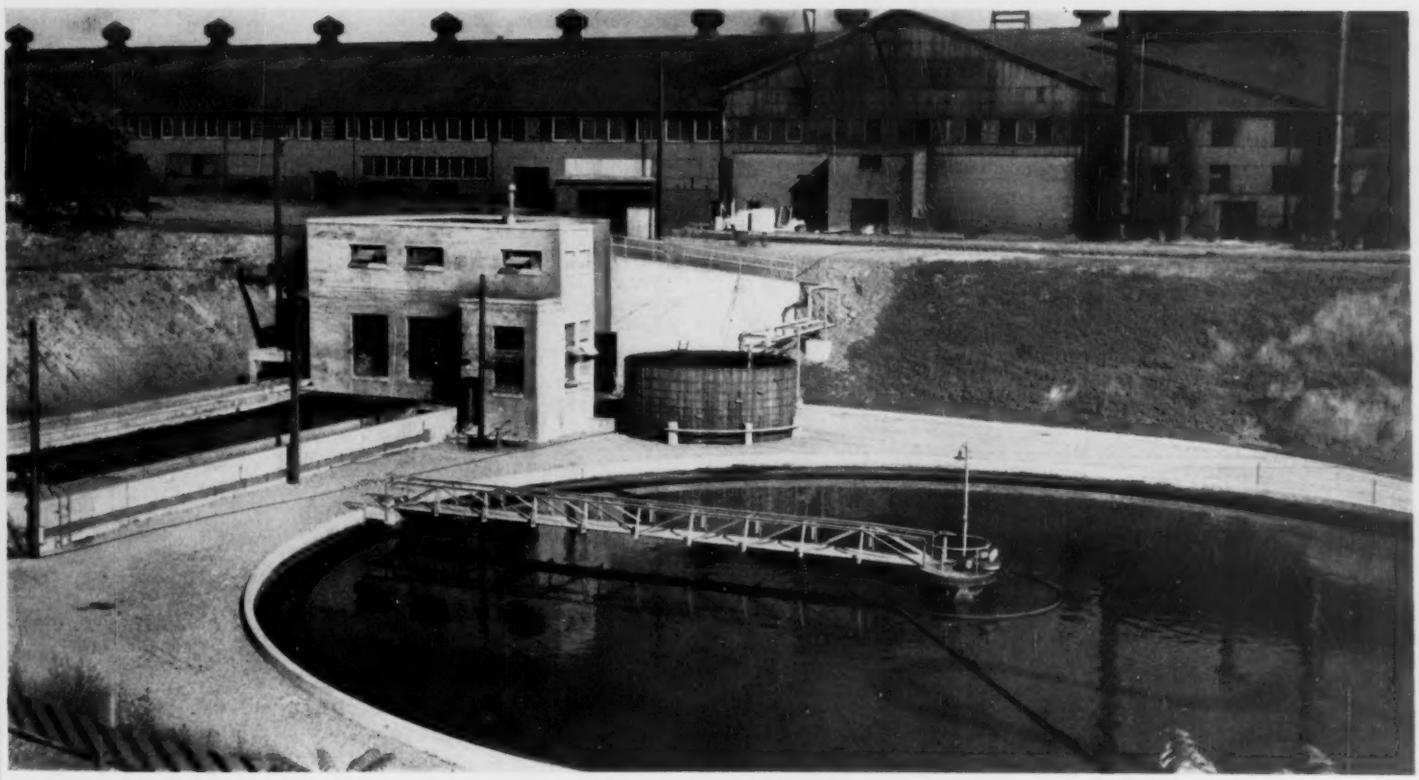

FIGURE 38.—*Industrial treatment plant.*

used widely for water purification. The amount required varies according to the impurity of the water. It is generally recognized that some excess should exist after oxidation of organic material is completed.

Aeration has been used in water purification since the earliest times. It has been used to treat ground waters with a high content of materials such as iron and manganese, and for the dissipation of dissolved gases having offensive tastes and odors. Water is most often aerated by spraying through fountains, but some times by mechanical means or with compressed air. Materials such as hydrogen sulphide, iron, and carbon dioxide are sometimes removed by aeration. Neutral, soft, or weakly alkaline waters containing little or no organic matter respond most favorably to treatment by aeration. In cases where iron cannot be removed by aerating, it may be precipitated at low pH value with aluminum sulphate as ferric salts after chlorination, or at high pH with lime or soda supplemented with the addition of iron salt and followed by chlorination (figure 37).

Four water softening methods often used are as follows:

1. Precipitation of hardness components with lime with subsequent introduction of substances to cause flocculation.

2. Waters of comparatively high noncarbonate hardness can be treated with lime and soda ash to effect precipitation, with the subsequent addition of substances to cause flocculation.

3. Precipitation with sodium phosphate is ordinarily used for special treatment in conjunction with 1 or 2 because of the high cost of this form of treatment.

4. Medium hard waters may be treated by passing through zeolites. Zeolite may also be used as an after-treatment to 1 or 2.

The choice of method will depend on the water composition, allowable hardness, and the cost. Hardness can be completely removed by 3 or 4 but only reduced to a hardness of about 30 parts per million by 1 or 2. As a rule, hardness of 70 parts per million will be satisfactory.

Coagulation is necessary in many waters because of the organic matter present. The precipitants most often used are alum and iron salts. For reasons of economy, sulfates and chlorides are usually used. In order to hasten the flocculation it is important that the colloidal particles first formed come into intimate contact with one another. This contact is often facilitated by stirring.

Some of the methods used to prevent corrosion are the application of a protective cover of paint, cement, coal-tar preparation, etc., the use of metals resistant to corrosion, or by correcting the water chemically. Oxygen may be reduced by preheating the water, but this method would probably be applicable mostly to boiler waters, or processes using hot water. Dissolved gases are removed from waters in some industries by the use of vacuum or by heat and pressure. Residual oxygen in water may be removed by chemicals such as ferrous hydroxide or sodium sulfite, or by the use of iron scrap, zinc scrap, or carbon and zinc together. Lime is often applied as an inhibitor of corrosive attack by waters containing dissolved gases (fig. 38).

Cost of Water for Industrial Use

General statistics on the cost of water to industry are not available. Occasional reports in the literature are available but do not lend themselves readily to generalization.

Processes used in treating water follow similar patterns whether the ultimate use is in industry or for municipal supplies. Because of this, and since a large segment of industry purchases water from municipal sources, it is estimated that the unit cost of water will range in the order of magnitude of the cost in a representative group of cities across the Nation.

Table 12 provides data on the cost of water per ton in cities. This compares with an oft quoted national figure for municipal supplies of 5 cents per ton of water.

Although the cost of water for domestic purposes is cheap, the factors of large volumes of water per unit of finished product, the degree of competition in the industrial area concerned, and the usual practice of having to treat highly polluted water in industrialized and urbanized areas, make the cost of industrial water a significant part of the economics of industry.

TABLE 12.—*Average unit cost of water in 14 of the largest United States cities (9)*

City	Cost, cents per ton
San Francisco	10. 92
Baltimore	6. 29
Los Angeles	5. 98
Pittsburgh	5. 57
Buffalo	5. 43
Boston	4. 99
Washington	4. 93
New York	4. 79
St. Louis	4. 66
Detroit	4. 06
Philadelphia	3. 84
Cleveland	3. 46
Milwaukee	3. 32
Chicago	1. 92
Average	5. 01
Median	4. 86

NOTE.—Bills are for water measured through a five-eighths-inch meter. Unit costs are derived from the average of 4 separate annual water bills. The 4 bills used are for quantities of 30,000 gallons (4,000 cubic feet or 125.2 tons), 45,000 gallons (6,000 cubic feet or 187.8 tons), 60,000 gallons (8,000 cubic feet or 250.4 tons), and 112,500 gallons (15,000 cubic feet or 469.4 tons).

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Industrial Uses of Water in the United States

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The aggregate volume of water used in public water systems is relatively small. For the entire United States it is approximately 10 percent of the flow of the Niagara River. The total domestic and industrial use of water from public supplies is near one-fifth of that used by irrigation, amounting to about 15,000 million gallons (44,000 acre-feet) per day of which one-third, more or less, is used by industry. In addition, industries develop for their own use approximately 5,000 million gallons (14,700 acre-feet) per day, together with still larger quantities of recirculated and sea water.

There are four sources of water upon which industry must depend to meet its present and future requirements. These are (*a*) surface water, (*b*) underground water, (*c*) sea water, and (*d*) water reclaimed from industrial and domestic sewage.

Industry's Specific Water Uses

The quantity and quality of water requirements for miscellaneous industries vary so widely that each type of processing presents individual requirements which must be satisfied. However, practically all industrial uses of water fall within one or more of the classifications listed in the following groups:

(a) Cooling.

(b) Processing (entering into or contacting products manufactured).

(c) Power generation.

(d) Sanitary services.

(e) Fire protection.

(f) Miscellaneous (air conditioning, washing, etc.).

Of these uses the demands for cooling water far exceed all others. For example, large individual electric generating stations will use 500,000 gallons of water per minute, or more, for surface condenser operations. It is obvious that such volumes of water are not obtainable from underground sources but well water is frequently supplied as make-up water to cooling towers to replace evaporation losses.

In the absence of cooling towers, the large volumes of water needed for cooling must be obtained from fresh surface water or salt-water sources. Where the surface water supply is limited, the effects of the withdrawal and return of cooling water to lakes and rivers may materially increase the temperature and thereby degrade the value of the water for other uses. The Mahoning River furnishes a good illustration where the river water temperature consistently averages 20° above the air temperature throughout the year. This is caused by constant use and reuse of this supply for cooling over a limited section of the river's course.

Usually the volume of water actually entering into a finished marketable product is a small portion of the total quantity consumed. A canning company using as much as 2.2 billion gallons of water per year estimates that less than 6 percent of this quantity, or 132 million gallons, actually contacts the processed food in such manner that it could become part of the food product. A much larger percentage of the total volume of water used does come in contact with the food during such preparatory processes as washing and soaking. Water to cool cans must be of good chemical quality and sterile to safeguard the flavor of the product and avoid contamination.

Importance of Large Water-Using Industries

A complete catalog of water consumption by the many units in each industry would be a hopelessly long and difficult task, but there are statistics available from which fairly good estimates can be made. The Census of Manufacturers referred to above includes not only the dollar volume, payroll data, etc., but also production in units appropriate to the industry. Experts in the field of water supply and industrial waste have established rates of water consumption per unit of production for most of the industries. These two sources of information have been combined to prepare the estimate of water consumed by various industries for the year 1947, which is shown in table 13.

The total of table 13 accounts for nearly 7,800,000 million gallons per year, or water usage at the enormous rate of over 21,000 million gallons per day.

The quantity of water required for each dollar of "Value added by manufacture" varies widely in the industries for which data are available. In the first four groups, where 500 to 1,400 gallons of water are required for each dollar of value added, cost of supply and treatment are of predominant importance. These industries must consider water supply to be a major limiting factor in their planning and development. On the other hand, in such industries as textiles,

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TABLE 13.—*Estimation of water usage by 20 selected industries*

DATA FROM 1947 CENSUS OF MANUFACTURERS

Industry	Number of establishments	Value added by manufacture	Production		Estimated water consumption	
			Number	Units	Gallons per unit	Million gallons
		Thousands				
Steel (finished)	419	$2, 659, 250	61, 857, 241	Tons	65, 000	4, 020, 721
Oil refining	437	1, 494, 474	1, 887, 890, 000	Barrels	770	1, 453, 675
Gasoline		[1]	791, 325, 000	do	357	791, 325
Wood pulp:						
Sulfate		[1]	5, 356, 710	Tons	64, 000	342, 829
Sulfite		[1]	2, 795, 960	do	60, 000	167, 758
Soda		[1]	491, 580	do	85, 000	41, 784
Ground wood		[1]	2, 049, 814	do	5, 000	10, 249
Total	226	415, 938				562, 520
Paper		[1]	10, 646, 833	Tons	39, 000	415, 226
Paper board		[1]	9, 186, 810	do	15, 000	137, 802
Total	665	1, 050, 108	19, 833, 643	Tons		553, 028
Coke	167	[1]	79, 146, 000	do	3, 600	284, 493
Beer	440	808, 946	88, 027, 000	Barrels	470	41, 373
Whisky	226	472, 357	246, 443, 000	Gallons	80	21, 155
Milk, cream and butter [2]		[1]	72, 440, 000, 000	Pounds	0. 11–0. 25	14, 286
Canning and preserving (excluding fish) [3]	2, 265	609, 939	391, 546, 000	Cases	7. 5–250	8, 520+
Manufactured ice [4]	3, 423	226, 584	36, 100, 000	Tons	243. 85	8, 802
Soft drinks	5, 618	421, 000	927, 700, 000	Cases	2. 5	6, 250
Woolens and worsted fabrics	495	599, 534	464, 563, 000	Pounds	70	3, 252
Wool scouring	74	54, 166	210, 172, 000	do	1. 26	2, 648
Tanning	561	403, 783	238, 731, 000	do	8	1, 910
Soap	249	450, 721	4, 138, 001, 000	do	0. 25	1, 034
Meat packing (hogs)	2, 153	[1]	51, 678, 047	Hogs	11	568
Cane sugar [5]	25	98, 112	358, 000	Tons	1, 000	358
Rayon (all types)	38	447, 900	746, 900, 000	Pounds	0. 16	119

[1] Value added by manufacture is not given on the same basis as production on which water consumption is based.
[2] Based on U. S. Department of Agriculture's figures for creamery butter, liquid milk and cream sold in communities. No other milk products subject to water consumption estimates.
[3] Estimate of 8,520 million gallons include water used in processing only 14 fruits and vegetables for which consumption factors are available. This accounts for 177,321,000 cases. Total water used by this group is probably 2 or 3 times as high.
[4] Includes filling cans and pulling cores.
[5] Includes refining only.

beverages, and others, the relations of water consumption to value of product is so small that more elaborate treatment can be justified.

Plant Location and Underground Water Supply

The location of many industries has been dictated largely by the availability of an ample underground water supply. This is particularly important to industries using cold well water for critical cooling purposes. As an alternate to uniform, cold, ground water, expensive refrigeration would be required.

Excessive withdrawal of ground water in localized areas can, and has, caused water shortage which results in economic difficulties. A typical example of such depletion occurred in Louisville during World War II. This condition was brought about by the establishment of synthetic-rubber industries in the area. These materially increased the existing heavy pumpage of established industries in this section. The combined effect was a rapid lowering of the ground-water table.

It should not be concluded that a decline of water level in a well field necessarily indicates an exhaustion of supply as some lowering is, of course, necessary in order to obtain the maximum safe yield from any aquifer.

Similar conditions have been experienced elsewhere in this country. An additional illustration is the lowering of the ground-water table by the withdrawal of water from deep wells in the Texas City area. In 1930 approximately 0.5

million gallons daily was withdrawn from the water-bearing aquifer; 15 years later the ground-water pumpage had increased to over 23 million gallons per day. In 1945 the measurements at one well 1,000 feet deep showed that the water table had receded to 102 feet below sea level. This draw-down not only increased the salt content of the ground water but resulted in dewatering of the sands in one section, at a rate of 2.4 inches per year. In some critical, but limited sections of the area, the subsidence has amounted to 1½ feet.

Based on these observations and conclusion, a constructive program for the conservation of ground water is suggested. This is as follows:

1. Scientific investigation of our ground-water resources.
2. Wide dissemination of the resulting data and principles.
3. Formulation of sound legal means of effecting desirable ground-water control.

Factors Responsible for Water Shortages

Basically, the conditions responsible for water shortages to meet community requirements are:

(*a*) Failure to provide for equalization of surface water run-off.

(*b*) Overconcentration of population and industries.

(*c*) Withdrawal of water from underground aquifers in excess of natural recharge.

(*d*) Water wastage.

(*e*) Failure to use available salt water in place of fresh water.

(*f*) Selection of plant sites without adequate evaluation of availability of water for existing or predictable future requirements.

(*g*) Inadequate design and planning of water-consuming processing equipment.

Water Wastage

Much of the distress from declining water supplies could be greatly curtailed by reasonable economy and drastic control of water wastage. Millions of gallons of water now being wasted can be stopped by reasonable conservation. In all cases where conservation methods have been practiced, the cost of supervision and control has been fully compensated for by dollar savings.

The American people, individually and collectively, have become the most wasteful Nation in the world. This habit is demonstrated by the use of both surface and underground waters. Our wastage of water is strikingly illustrated by a comparison of the per capita consumption of water in cities in Europe and in this country. The average per capita water rate in 10 European cities, including London, Paris, Vienna, Edinburgh, and Berlin, before World War II, was 39 gallons per day, while in the same number of cities in this country it was 155 gallons per day. In the latter group are New York, Philadelphia, Baltimore, Chicago, Detroit, and others.

The existing water shortage in New York City is in part added proof of extravagance and the urgent need for concerted effort to curtail water wastage. Water conservation by industries and all other groups will be reflected in savings which are commensurate with the efforts made to avoid waste. Beyond the immediate financial return resulting from such action, there are the larger and more comprehensive benefits to be gained, such as the effect on the growth and development of communities and the over-all welfare of the inhabitants. Without adequate water, specific limitations are imposed which retard the growth of all civic and industrial expansion.

Value of Flood Control Measures To Provide Satisfactory Industrial Water

Flood control projects have been established primarily to avert disaster from flood waters, but there are many resulting contingent benefits. Although not fully realized, conservation of flood water has a far-reaching effect, not only in minimizing water shortages for industrial requirements but in improving water quality. By stream flow control, the effect of depreciation of water quality by industrial and sanitary wastes is reduced in accordance with the degree of regulation. One of the most direct benefits resulting from such regulation is the prevention of salt water intrusion into tidal rivers. It is a well known fact that salt water penetration into many fresh water streams results from insufficient river flows. During the severe drought of 1930 and 1931, the salt content in the Delaware River at Chester, Pa., rose to 1,860 parts per million. This location is approximately 20 miles upstream from the mouth of the river. Normally, the salt content of the river in this area is less than 25 parts per million. Such conditions are reflected directly in the cost of treatment of the supply.

Substitution of Salt Water for Fresh Water

Many of industry's water requirements can be adequately fulfilled by salt water where such supplies are available. To safely use brackish water, industrial equipment must be fabricated of material to resist the aggressiveness of the water. Many water shortages now existing in the seaboard area and in locations where underground salt water is available, could be minimized or completely corrected merely by the use of the available salt water. No plant in a water critical area should be designed to operate solely on fresh water when salt water is available. Obvious as is this water conservation measure, many seaboard plants use no salt water. The principal reason for failure to utilize such water is the increased cost of corrosion-resisting materials. Over an extended period of

time the use of salt water for many purposes can usually be justified, regardless of higher capital investments involved.

Laws Relating to Conservation of Underground Waters

Many laws relating to some phases of the withdrawal of underground waters are on the statute books but such regulations are either inadequate or not enforced in many critical areas. However, there is a gradual awakening with regard to the need for this type of important legislation. Any program for the conservation of water resources which may be developed on a national scale requires meticulous investigation into the needs of the various States, or areas of the country so that local requirements may be coordinated with national conservation policy.

Corrective Program

The water demanded for our expanding industries can and must be provided. The solution of the problem, involving as it does complex economic aspects, may only be found by an enlightened viewpoint reflected by industrial management and equitable, reasonable regulations. Such regulations must be imposed by mutual agreement and cooperative effort among those affected and by constructive long-term planning by municipal and State regulations. Within the last few years, aroused public concern over these deficiencies has prompted the assembly of much information on the subject. However, there are still many deficiencies. The data thus far compiled must be assembled and additional information collected before an accurate evaluation of the problem can be made and controlling measures established.

Studies in locations in which the water supply conditions are actually or potentially critical demonstrates the need for the inauguration of a program including:

1. An inventory of water requirements on a national basis coordinated with actual and potential water resources available, including both surface and groundwaters. This survey should be both local and area-wide with respect to major river basins and geological formations.
2. Making available factual data regarding overindustrialization within critical, or potentially critical, water areas and the desirability of decentralization of industrial users of large volumes of water.
3. A study of the inter- and intra-State control and regulation of flood waters to provide present and future industrial water requirements, regardless of other benefits accruing from such facilities.
4. Promotion of salt water usage as a conservation measure.
5. Expanding the activities of the State and Federal agencies handling critical underground water resources problems.
6. Providing technical personnel for the United States Geological Survey and comparable State organizations, together with the necessary funds to effect more adequately utilization of the valuable services of these organizations.
7. Coordinating the activity of waste disposal regulation groups with those interested in resources.

Use of Water for Irrigation

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Historical Development

IT HAS BEEN SAID that the art of irrigation is so old that its origin is lost in antiquity, but that the science of irrigation is a modern development which is still advancing rapidly. Prior to the introduction of so-called modern irrigation into the West by the Mormons in 1847, irrigation had been practiced in North America by at least three different cultures.

The first recorded irrigation development occurred thousands of years ago under a prehistoric race in New Mexico. Based on the structures which have been uncovered from old lava beds such as reservoirs, aqueducts and canals, this culture was well advanced in engineering skill. Apparently the advances which were made at this time were lost to subsequent civilizations.

The second known irrigation development occurred under the Pueblo Indians a thousand or more years ago. The acreage developed was not large and it was confined to the valleys near the cliff or community dwellings in Arizona, New Mexico, southwestern Colorado, and Utah. The traces of this development which still remain indicate that it was much more primitive than the earlier development.

The measures developed under the Pueblo Indians were followed subsequently in a large measure by Mexicans of Spanish-Indian origin who gradually extended their settlements from the south northward to Colorado along the Rio Grande, Pecos and Arkansas Rivers and their tributaries. This culture, however, was influenced by the culture which was introduced by the Moors into Spain in the eighth century and subsequently by the Spanish missionaries into Mexico and then northward in the sixteenth century. Irrigation was practiced also around the early missions on the Pacific coast. Some of these Franciscan missions developed extensive and well integrated agricultural communities. The limited written records of this era indicate that irrigability was based on engineering feasibility rather than the suitability of the land to irrigation.

The development of the so-called modern irrigation beginning in 1847 in Utah was under people with northern and central European ancestry which had no tradition or experience in irrigation and consequently it was developed largely by trial and error. Nevertheless, irrigation ultimately became well established and subsequently was extended rapidly throughout the Western States.

Importance of Irrigation in Western Development

Irrigation is not only a major but an essential purpose in western water resource development. This is true because (1) the 17 Western States contain approximately 22 percent of our population and the anticipated rate of increase is much greater than for the country as a whole, (2) these States contain essentially 60 percent of our land area and the proportion devoted to cultivated crops is only one-half of that for the remainder of the country, and (3) about 1 acre of 10 of the arable land in these States is irrigated, the yields from which are twice those from the nonirrigated land and 50 percent greater than the national averages. Thus, water must be recognized as the limiting factor in the development of the West.

The development of irrigation has been and remains vital to the development of the West. Development beyond that which its limited water supply will support cannot be anticipated. Although the use of water for irrigation is of paramount importance, a balance must be found with the competing uses for domestic and industrial consumption, power development, fish and wildlife conservation, recreation, navigation and related purposes. Water initially considered primarily for use in irrigation, has not only retained this importance but has assumed even greater importance because of its role in multiple-purpose projects and in regional development. In serving these purposes it also contributes to the national economy and security.

The purpose of the Reclamation Act of 1902 was to create farming opportunities in the arid West and in this respect it was a reaffirmation of the objectives of the Homestead Act of 1862. During the period prior to passage of the 1902 act the easily accessible water supplies available by simple diversion of natural flow were developed by the early homesteaders. For areas removed from the immediate streams, or where storage was necessary for reclamation, more capital and credit was required than was commonly possessed by the home seekers. As the lands most easily irrigated passed rapidly into private home ownership, the latecomers found

themselves confronted with tasks enormously greater than that of their predecessors, and far beyond their means. Thus, opportunities for establishment of new farm homes would have disappeared without the public action that was undertaken to encourage development of the desert lands.

Under the initial Reclamation Act, contracts were executed with individual water users providing for the repayment of their individual share of project construction costs in 10 annual installments. Difficulties in meeting the payments ever so short a period led to the passage of the Reclamation Extension Act in 1914, which permitted the period of repayment to be extended to 20 years. The acts of 1911 and 1922 authorized negotiation of repayment contracts with water users' organizations and in 1926 the laws were further revised to require repayment contracts thereafter with water users' organizations. The irrigation payout period was lengthened to 40 years in the Omnibus Adjustment Act of 1926. The Reclamation Project Act of 1939 represented a significant departure in the payment arrangements for reclamation projects. Cost allocations were authorized for multiple-purpose projects, whereby irrigation was relieved of the responsibility of repaying total project costs, and required to return only the costs allocated to and assigned for repayment by irrigation. Nonreimbursable cost allocations were authorized for flood control and navigation. Reimbursable cost allocations were authorized for irrigation, for power, and for municipal and industrial water. The repayment contract payout period of 40 years was retained, but in addition utility-type water service contracts were authorized. The principle of interest-free money was retained with respect to costs allocated to irrigation. Finally nonreimbursable cost allocations to fish and wildlife conservation were authorized in 1946.

Thus, the objectives of the original act have been broadened to encompass balanced resource development which is essential not only to the expanding economy and population of the West, but to the entire Nation.

Present Acreage and Location of Irrigated Lands

Approximately 20.5 million acres of land in farms were irrigated in 1944 (table 14). Nearly 95 percent of this acreage was located in the 17 Western States and the greater part of the remainder was located in the three States of Arkansas, Florida, and Louisiana. It is estimated that the acreage of irrigated land in the Western States had increased to 21.5 million acres in 1948. Supplemental irrigation in the more humid areas has had an interesting but erratic development. Although some land has been irrigated every year in most of the Eastern States for the past 50 or more years, the total has been relatively unimportant until recent years. Current estimates indicate that the amount may now be in excess of 500,000 acres not including the approximately 1,000,000 of irrigated rice. It is possible that the 1950 census will show further increases.

TABLE 14.—*Distribution of irrigated lands by States in 1944*

State	Acres	Percentage
Arizona	736, 000	3. 6
California	4, 953, 000	24. 1
Colorado	2, 699, 000	13. 1
Idaho	2, 026, 000	9. 9
Kansas	96, 000	. 5
Montana	1, 555, 000	7. 6
Nebraska	632, 000	3. 1
Nevada	674, 000	3. 3
New Mexico	535, 000	2. 6
North Dakota	23, 000	. 1
Oklahoma	2, 000	
Oregon	1, 129, 000	5. 5
South Dakota	53, 000	. 2
Texas	1, 320, 000	6. 4
Utah	1, 124, 000	5. 5
Washington	520, 000	2. 5
Wyoming	1, 354, 000	6. 6
17 Western States	19, 431, 000	94. 6
Arkansas	289, 000	1. 4
Florida	222, 000	1. 1
Louisiana	536, 000	2. 6
All other States	61, 000	. 3
United States	20, 539, 000	100. 0

[1] The 1945 U. S. Census of Agriculture. This estimate which is slightly lower than the acreage reported by the 1940 Census of Irrigation probably represents a difference in methods of enumeration rather than a decrease in acreage.

Utilization of Irrigated Lands

Many types of crops ranging from very intensive high value to extensive low value crops are grown on irrigated land. The three most important crop groups are (1) hay, forage, and pasture crops; (2) cereal crops; and (3) vegetable, fruit, and nut crops. The crops in these three groups occupy more than 80 percent of the total irrigated land with the hay, forage and pasture crop the most important group. The high acreage maintained in this group of crops is not only conducive to maintenance of productivity, but also to stabilization of the economy through its influence on the production of livestock and livestock products. The vegetable, fruit and nut crop acreages are made up of many types and varieties of crops and represent the most intensive type of use. Sugar beets and cotton also are crops of considerable importance. The percentage distribution of the various types of crops grown on irrigated land is shown in table 15.

Although there is some change from year to year, and in the averages shown in the table, the proportions of irrigated land devoted to the various kinds of crops remain relatively constant. The slight trends shown for the vegetables, fruits, and nuts, for sugar beets and for cotton and the shifting between the cereal crops and the hay, forage,

TABLE 15.—*Percentage distribution of the various types of crops grown on irrigated land* [1]

Crop or crop group	U. S. census 1939	Annual crop census, Bureau of Reclamation			
		1939	1937–39	1940–44	1945–49
Hay, forage, and pasture	51. 7	44. 8	41. 4	45. 1	42. 7
Cereals	24. 4	21. 7	23. 0	21. 4	23. 4
Vegetables, fruits, and nuts	12. 3	13. 8	13. 9	15. 2	16. 3
Sugar beets	3. 5	6. 1	5. 8	4. 8	4. 8
Cotton	4. 3	6. 8	8. 9	6. 3	5. 6
Miscellaneous	3. 8	6. 8	7. 0	7. 2	7. 2

[1] The percentage distribution shown for the 1940 U. S. Census of Irrigation is based on approximately 18 million acres whereas that for the Annual Crop Census of the Bureau of Reclamation is based on an annual acreage of about 2 million. Bureau of Reclamation data prior to 1937 are not available in comparable form.

and pasture crops may have more significance, however, than indicated by the magnitude of the changes (fig. 39).

Productivity of Irrigated Lands

It is estimated that yields per acre from irrigated cropland will on the average exceed yields per acre for all cropland in the United States by 50 percent.[1] It should be recognized, however, that the productivity of irrigated land varies widely and in accordance with climatic conditions, the quality of the land and the adequacy and quality of the water supply. Practically the full production on irrigated land in the more arid areas results from the application of water. In the more humid areas, the increment in

[1] Based on yields of 8 principal crops for the 10-year period 1935 to 1944 as reported for the United States in 1948 Agricultural Statistics, U. S. Department of Agriculture and for irrigated land in the Annual Crop Census, Bureau of Reclamation, U. S. Department of the Interior.

FIGURE 39.—*Irrigation, lettuce, Imperial Valley, California.*

production which may be attributed to the application of irrigation water is more variable and may range from relatively small to the total crop depending upon the amount and distribution of the precipitation. The increasing attention which is being directed toward irrigation in the more humid areas is evidence of its value in such areas.

The yields of specific crops on irrigated land in the 17 Western States and in Arkansas and Louisiana for 1939 were from one-third to over three times higher than the yields of the same crops on nonirrigated land. For all crops, yields from irrigated land were more than double the yields from nonirrigated land.[2] In another comparison, yields per acre irrigated for five standard cereal crops in Colorado during the period 1928 to 1937 averaged approximately three times as much as the yields of the same crops obtained without the use of irrigation water.[3]

For the past several years, the value of the crops produced on land receiving water from facilities constructed by the Bureau of Reclamation has averaged over $100 per acre. In 1949, crop values ranged by projects from approximately $25 to $650 per acre. These values represent primarily a difference in growing season, type of crops, and intensity of use.[4]

The economic importance of this increased production may be expressed in the form of out-shipments and in-shipments associated with project development. As an illustration the Salt River Valley project area of Arizona shipped out 35,000

[2] 1940 U. S. Census of Agriculture.

[3] Field Crops in Colorado, Warren H. Leonard and Robert S. Whitney, third edition, 1950 (processed).

[4] 1949 Crop Summary and Related Data, Federal Reclamation Projects, Bureau of Reclamation, U. S. Department of the Interior.

FIGURE 40.—*Irrigation, sugar beets, Buffalo Rapids project, Montana. (Priming siphon tube).*

carloads of agricultural products in 1949 valued at $73 million and received over 50,000 carloads of various commodities valued in excess of $188 million. Most of the commodities shipped in were manufactured goods from the eastern and midwestern markets. On the basis of data collected from certain other projects, it is estimated that total in-shipments to Federal reclamation areas in 1948 amounted to $1,700 million.

Present Status of Project Development

Approximately 92,000 irrigation enterprises including individuals and partnerships, had an investment of over $1 billion in project facilities and provided water to 21,000,000 acres in 430,000 farms in 1939. These results by types of enterprise are summarized in table 16. By 1949, water was supplied from facilities constructed by the Bureau of Reclamation to approximately 4.8 million acres of land. These facilities were adequate to serve an additional area of approximately 850,000 acres. This includes land in rights-of-way and nonproductive farm use and land which has not been developed because of the normal lag in development and because some of the land in the earlier projects has been found unsuitable for irrigation development. The total Federal investment in these facilities including those for other project purposes such as power, municipal water and flood control amounts to approximately $1.5 billion.[5] The irrigated lands in non-Federal projects represent for the most part the earlier developments which had rather readily available water supplies and individual developments such as those resulting from direct stream diversion or pump irrigation. The investment in these facilities, as shown in table 16, amounted to approximately $800 million in 1939, the last year for which estimates are available.

[5] The Reclamation Program, 1950-56, Bureau of Reclamation, U. S. Department of the Interior.

FIGURE 41.—*Irrigation, almond grove, Sacramento Valley, Calif.*

TABLE 16.—*Investment in various types of irrigation enterprises and number of enterprises with number of farms and acres served* [1]

Type of enterprise	Total investment (000)	Number of enterprises		Area served	
		Total	5 or more units	Farm units	Acres (000)
Individuals and partnerships	$187,383	86,050	1,093	90,037	7,314
Cooperatives	224,141	4,356	3,701	148,294	6,652
Irrigation and reclamation districts	268,151	441	433	108,338	3,574
Bureau of Reclamation [2]	250,245	97	96	43,517	1,824
Commercial	66,244	275	239	19,210	1,018
Indian	48,420	188	117	15,254	516
Other	7,465	230	53	5,372	106
Total	1,052,049	91,637	5,732	430,022	21,004

[1] From the 1940 U. S. Census.

[2] Does not include acreages served with supplemental water since the latter areas are represented in other classifications, but the construction costs of facilities under contract to provide such supplemental water are included in the investment.

Potential Irrigation Development

The Bureau of Reclamation has estimated that there is sufficient water available to provide 16,695,000 additional acres of land with a full supply and to provide 8,706,000 acres of presently irrigated lands with supplemental water.[6] These estimates were based on recognized requirements for engineering feasibility but did not consider the economic feasibility or justification for individual projects. Neither did they take into account the development which might be accomplished under unrestricted transbasin diversions of water.

Converting the above estimates of 16,695,000 and 8,706,000 acres to the average cropland equivalent for the United States on the basis of the following assumptions: (1) 3 acres receiving a supplemental water supply equaling 1 acre receiving a full supply, (2) 25 percent of the land being retained in pasture and 3 acres of pasture land equaling 1 acre of cropland, and (3) the yields of irrigated land exceeding average yields for the United States by 50 percent would result in approximately 25 million acres of average cropland equivalent.

[6] The Reclamation Program, 1950–56, Bureau of Reclamation, U. S. Department of the Interior.

An estimate by the National Resources Board in 1934 placed the ultimate acreage that could be irrigated in the 17 Western States at 51.5 million acres.[7] Based on this estimate, there would remain approximately 30 million susceptible of development.

The rate of development of these lands will be contingent upon many factors and the above estimates should be considered as approaching the upper ultimate limit rather than being attained within the foreseeable future. Based on present authorizations, programing, and past experience, the bringing in of 6 million acres of irrigated cropland equivalent into full production by 1975 or 9,000,000 acres of average cropland equivalent would appear possible of accomplishment. In addition to this some further development of land now provided with facilities may be anticipated as well as some further increase in pump irrigation and in development of various types of irrigation facilities throughout the Eastern States. Likewise, water may be conserved and production increased on existing projects by more efficient use of water through (1) rehabilitation of the facilities such as lining the canals, thereby saving water; (2) avoiding overuse of water, thereby not only increasing yields on the land concerned but saving water for use elsewhere; and (3) saving or salvaging water that is lost or transpired through noneconomic plants such as salt cedars and other types of vegetation and by treatment of sewage. Although firm estimates pertaining to such potential savings are not available, significant amounts of water can be conserved frequently at relatively low cost. As an illustration, it has been estimated that 40,000 acre-feet of water can be conserved in the Mojave River Basin in California by eradication of cottonwood trees.

The reclamation program for 1950–56 encompasses the providing of a full supply of water to 1,613,700 acres and supplemental water to 2,919,800 acres at a total cost of $2,165,686,000 for project facilities including those for power, flood control, and other purposes. To complete the projects involved in this program would provide a full water supply to an additional 5,775,000 acres and supplemental supply to 1,363,300 acres at an additional cost of $1,861,451,000. Completion of this total program would provide approximately 7.4 million acres of irrigated cropland equivalent or somewhat more than that which appears possible of accomplishment by 1975. It is not possible to provide estimates of the time of completion or costs of the remaining land considered susceptible of irrigation development.

[7] National Resources Board report, December 1934, p. 129.

Status of Hydroelectric Power Development in the United States

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The status of hydroelectric power development in the United States as of January 1951 with respect to existing developments and estimated undeveloped power is presented in the following tables and accompanying text.

Existing Hydroelectric Power in the United States

Generating capacity installed in the existing hydroelectric power plants in the United States as of January 1, 1951, and the generation in 1950, based on figures available at time of compilation are shown in table 17. These data are subdivided by classes of ownership for the nine geographic divisions and for the United States as a whole. The classes of ownership are private utilities, Federal, non-Federal public, and industrial.

The aggregate installed capacity on January 1, 1951, was 18,667,426 kilowatts. The generation in 1950 was 101 billion kilowatt-hours, or about 5,400 kilowatt-hours per kilowatt. This indicates an over-all national plant factor of 61.7 percent, in comparison with 51.3 percent for fuel-electric plants.

The aggregate installed hydroelectric capacity of 18,667,426 kilowatts amounted to 22.7 percent of the total 82,411,018 kilowatts of all types of prime movers, hydro and fuel-electric. The aggregate hydroelectric generation in 1950 of 101 billion kilowatt-hours amounted to 26 percent of the total electric energy production of 388,087,731,000 kilowatt-hours during that year.

The installed capacity in privately owned electric utility hydro plants was 9,654,265 kilowatts or about 51.6 percent of the total. Federal and non-Federal public hydro installations amounted to 8,008,587 kilowatts or about 43 percent of the total. The 1,004,574 kilowatts of industrial installations account for 5.4 percent.

Hydroelectric Power Plants Existing and Under Construction

Table 18 shows hydroelectric power plants in operation or under construction as of January 1, 1951, in which it is planned ultimately to install generating capacity of 100,000 kilowatts or more. The table shows for each plant the river basin and State in which it is located, present or initial installed capacity, planned installed capacity, average annual generation with ultimate installation, and regulatory storage.

The existing 8,896,690 kilowatts of installed capacity in the 46 larger plants is 48 percent of the total 18,667,426 kilowatts installed in the United States as of January 1, 1951. This percentage will increase since the aggregate ultimate installations for all the smaller plants now under construction will be only about 1,000,000 kilowatts, whereas the large projects now under construction will add 4,456,500 kilowatts of power to the installed hydroelectric capacity during the next few years. The planned ultimate capacity of 17,162,755 kilowatts in the large plants now existing and under construction represents about 16 percent of the 106,271,000 kilowatts of total hydroelectric power capacity that can be developed in the United States according to estimates as of January 1, 1951.

Undeveloped Power for Selected River Basins

Table 19 compares the existing development as of January 1, 1951, and the undeveloped hydroelectric power for most of the principal river basins in the United States. The installations at existing plants in these basins total 14,659,524 kilowatts, or about 78 percent of the total now developed, and the corresponding average annual generation of these plants totals 78.4 billion kilowatt-hours, or about 81 percent of the total generation. The undeveloped generating capacity in these basins totals 71,289,000 kilowatts, or about 81 percent of the estimated aggregate undeveloped water power in this country. The corresponding estimated average annual generation totals 317.4 billion kilowatt-hours, or about 81 percent of the estimated aggregate.

The following have the largest existing development of hydro power resources: The Columbia River, with 3,208,676 kilowatts; the Tennessee, with 2,610,072 kilowatts; the Sacramento-San Joaquin, with 2,209,490 kilowatts; and the Colorado River Basin, with 1,328,678 kilowatts.

Undeveloped Hydroelectric Power in the United States

The estimates of undeveloped hydroelectric power in the United States are shown in table 20 and were prepared by the Federal Power Commission as of January 1951. The estimates of capacity represent a summation of the rated capacities of generators which would normally be installed at the sites where hydroelectric developments appear to be feasible, assuming regulation of flow by storage, allowance for depletions due to required consumptive use, and assuming that each site will be developed to achieve, in conjunction with the development of other sites, the best over-all development of the water resources of the river basin for power and multiple-purpose use. The estimates of generation represent a summation of the average annual generation of energy at these hydroelectric developments.

The estimates are based upon the best information available, as obtained from many different sources, and include projects at sites where physical conditions indicate engineering feasibility and promise of economic feasibility sometime in the future. In cases where sites are on interstate boundary sections of rivers the available power has been, in general, divided equally between adjoining States. At sites involving international boundaries one-half of the potential power has been divided equally. The estimates are subject to revision either by increase or decrease as additional information

TABLE 17.—*Existing hydroelectric power in the United States as of Jan. 1, 1951* [1]

INSTALLED CAPACITY—KILOWATTS

Geographic division (see note)	Privately owned electric utilities	Federal public power plants	Non-Federal public power plants	Industrial power plants	Total
United States	9, 654, 265	6, 448, 320	1, 560, 267	1, 004, 574	18, 667, 426
New England	938, 313		23, 608	268, 225	1, 230, 146
Middle Atlantic	1, 576, 890		25, 533	75, 602	1, 678, 025
East North Central	758, 032		70, 451	71, 113	899, 596
West North Central	424, 541		152, 744	57, 577	634, 862
South Atlantic	1, 821, 336	286, 600	188, 965	470, 595	2, 767, 496
East South Central	666, 985	2, 043, 400	10, 373	8, 000	2, 728, 758
West South Central	98, 620	148, 500	215, 959	3, 050	466, 129
Mountain	922, 327	1, 247, 420	108, 833	4, 013	2, 282, 593
Pacific	2, 447, 221	2, 722, 400	763, 801	46, 399	5, 979, 821
GENERATION 1950—1,000 KILOWATT-HOURS					
United States	50, 633, 631	38, 414, 272	6, 880, 222	4, 944, 793	100, 872, 918
New England	3, 585, 223		89, 682	1, 081, 368	4, 756, 273
Middle Atlantic	9, 833, 810		150, 276	355, 062	10, 339, 148
East North Central	3, 052, 619		291, 728	369, 768	3, 714, 115
West North Central	2, 275, 960		601, 645	272, 109	3, 149, 714
South Atlantic	7, 145, 403	1, 437, 951	699, 340	2, 555, 716	11, 838, 410
East South Central	3, 128, 663	12, 448, 407	37, 437	24, 700	15, 639, 207
West South Central	253, 210	531, 687	591, 601	8, 783	1, 384, 281
Mountain	5, 759, 196	6, 172, 544	457, 311	14, 325	12, 403, 376
Pacific	15, 599, 547	17, 823, 683	3, 961, 202	262, 962	37, 647, 394

NOTE

New England: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut.
Middle Atlantic: New York, New Jersey, Pennsylvania.
East North Central: Ohio, Indiana, Illinois, Michigan, Wisconsin.
West North Central: Minnesota, Iowa, Missouri, North Dakota, South Dakota, Nebraska, Kansas.
South Atlantic: Delaware, Maryland, District of Columbia, Virginia, West Virginia, North Carolina, South Carolina, Georgia, Florida.
East South Central: Kentucky, Tennessee, Alabama, Mississippi.
West South Central: Arkansas, Louisiana, Oklahoma, Texas.
Mountain: Montana, Idaho, Wyoming, Colorado, New Mexico, Arizona, Utah, Nevada.
Pacific: Washington, Oregon, California.

[1] Figures subject to minor revisions and adjustments when prepared in final form for publication.

becomes available concerning stream flow, reservoir sites, and other pertinent matters.

Some conception of the significance of the undeveloped water power in terms of present and prospective power supply may be obtained by noting that the 390 billion kilowatt-hours of undeveloped hydroelectric energy is approximately equal to the *total* production of 388 billion kilowatt-hours of electric energy in the United States in 1950. However, on the average, the plant factor of this hydro would be somewhat lower than the national plant factor in 1950.

TABLE 18.—*Hydroelectric power plants existing and under construction in United States with ultimate capacity of 100,000 kilowatts or more as of Jan. 1, 1951* [1]

FEDERAL POWER PLANTS

Name of plant	River	State	Installed capacity		Average annual generation ultimate (1,000 kilowatt-hours)	Regulatory storage [2] (1,000 acre-feet)
			Present or initial kilowatts	Planned ultimate kilowatts		
Grand Coulee	Columbia	Washington	1,640,000	1,974,000	14,000,000	5,212
Chief Joseph [1]	do	do	1,024,000	1,536,000	8,681,000	
Hoover	Colorado	Arizona-Nevada	1,034,800	1,332,300	5,348,000	22,144
McNary [1]	Columbia	Washington-Oregon	840,000	980,000	6,805,000	
Bonneville	do	Oregon	518,400	518,400	3,578,000	
Wilson	Tennessee	Alabama	436,000	436,000	2,492,000	70
Oahe [1]	Missouri	South Dakota	170,000	425,000	1,904,000	13,400
Garrison [1]	do	North Dakota	240,000	400,000	1,712,000	13,850
Shasta	Sacramento	California	379,000	379,000	1,965,000	3,200
Bull Shoals [1]	White	Arkansas	120,000	320,000	664,000	626
Fort Randall [1]	Missouri	South Dakota	160,000	320,000	1,236,000	2,450
Hungry Horse [1]	Flathead	Montana	285,000	285,000	1,176,000	2,980
Clark Hill [1]	Savannah	South Carolina-Georgia	280,000	280,000	703,000	1,340
Wolf Creek [1]	Cumberland	Kentucky	270,000	270,000	867,000	2,142
Wheeler	Tennessee	Alabama	259,200	259,200	1,244,000	328
Davis [1]	Colorado	Arizona	225,000	225,000	990,000	1,600
Pickwick Landing	Tennessee	Tennessee	144,000	216,000	1,329,000	239
Buggs Island [1]	Roanoke	Virginia-North Carolina	108,000	204,000	410,000	1,085
Fontana	Tennessee	North Carolina	135,000	202,500	850,000	1,157
Denison	Red	Texas-Oklahoma	70,000	175,000	300,000	1,814
Folsom [1]	American	California	162,000	162,000	503,000	890
Kentucky	Tennessee	Kentucky	160,000	1,160,000	1,160,000	721
Watts Bar	do	Tennessee	150,000	150,000	790,000	209
Norfork	White	Arkansas	70,000	140,000	168,000	706
Center Hill [1]	Caney Fork	Tennessee	135,000	135,000	328,000	492
Fort Loudon	Tennessee	do	128,000	128,000	530,000	82
Douglas	French Broad	do	86,000	112,000	406,000	1,358
Parker	Colorado	California	120,000	120,000	831,000	218
Cherokee	Holston	Tennessee	60,000	120,000	322,000	1,412
Hiwassee	Hiwassee	North Carolina	57,600	115,200	265,000	362
Palisades [1]	Snake	Idaho	67,500	112,500	521,000	1,200
Chickamauga	Tennessee	Tennessee	81,000	108,000	745,000	238
Allatoona	Etowah	Georgia	74,000	108,000	169,000	253
Fort Peck	Missouri	Montana	50,000	105,000	730,000	18,795
Norris	Clinch	Tennessee	100,800	100,800	400,000	1,761
Detroit [1]	North Santiam	Oregon	100,000	100,000	340,000	340
Total, 21 existing plants			5,753,800	6,959,400	37,622,000	
Total, 15 plants under construction.[1]			4,186,500	5,754,500	26,840,000	
Total, 36 Federal plants			9,940,300	12,713,900	64,462,000	

[1] Plants under construction.
[2] Total multiple-use storage is shown for Federal plants.

TABLE 18.—*Hydroelectric power plants existing and under construction in United States with ultimate capacity of 100,000 kilowatts or more as of Jan. 1, 1951* [1]—Continued

PRIVATELY OWNED HYDROELECTRIC POWER PLANTS

Name of plant	River	State	Installed capacity		Average annual generation ultimate (1,000 kilowatt-hours)	Regulatory storage [2] (1,000 acre-feet)
			Present or initial kilowatts	Planned ultimate kilowatts		
Safe Harbor	Susquehanna	Pennsylvania	230,000	388,000	920,000	63
Conowingo	do	Maryland	252,000	396,000	1,600,000	71
Shoellkopf	Niagara	New York	336,050	336,050	3,150,000	
Saluda	Saluda	South Carolina	130,000	195,000	200,000	1,600
Rock Island	Columbia	Washington	61,225	180,000	1,500,000	
Merwin	Lewis	do	91,000	180,000	456,000	246
Osage	Osage	Missouri	133,200	176,200	375,000	1,235
Keokuk	Mississippi	Iowa	117,600	149,600	1,000,000	128
Comerford	Connecticut	New Hampshire	140,400	140,400	310,000	27
Big Creek No. 3	San Joaquin	California	107,100	135,000	743,000	1
Martin	Tallapoosa	Alabama	99,000	132,000	400,000	1,375
Pit No. 5	Pit	California	128,000	128,000	826,000	
Jordan	Coosa	Alabama	100,000	125,000	550,000	44
Calderwood	Little Tennessee	Tennessee	121,500	121,500	540,000	4
Chelan	Chelan	Washington	48,000	120,000	467,000	676
Rock Creek	North Fork Feather	California	113,400	113,400	494,000	2
Kerr	Flathead	Montana	112,000	112,000	700,000	1,217
Holtwood	Susquehanna	Pennsylvania	111,000	111,000	590,000	19
Cheoah	Little Tennessee	North Carolina	110,000	110,000	517,000	2
Walters	Big Pigeon	do	108,000	108,100	306,000	20
White River	White	Washington	62,000	100,000	310,000	56
Total, 21 privately owned hydroelectric power plants			2,711,475	3,557,250	15,954,000	

NON-FEDERAL PUBLIC POWER PLANTS

Ross [1]	Skagit	Washington	270,000	360,000	847,000	3,000
Pinopolis	Santee	South Carolina	132,615	163,215	640,000	650
Gorge	Skagit	Washington	74,400	144,000	1,000,000	
Diablo	do	do	122,400	122,400	800,000	50
Total, 3 existing plants			329,415	429,615	2,440,000	
Total, 1 plant under construction.			270,000	360,000	847,000	
Total, 4 non-Federal public power plants.			599,415	789,615	3,287,000	

INDUSTRIAL POWER PLANTS

Hawks Nest	New	West Virginia	102,000	102,000	567,000	
Total, 46 existing plants			8,896,690	11,048,255	56,583,000	
Total, 16 plants under construction.			4,456,500	6,114,500	27,687,000	
Grand total, 62 plants			13,353,190	17,162,755	84,270,000	

[1] Plants under construction.
[2] Total multiple-use storage is shown for Federal plants.

TABLE 19.—*Developed and undeveloped hydroelectric power of selected river basins of the United States as of January 1951*

River basin	Existing development			Undeveloped power		Total		Percent of total capacity developed
	Number of plants	Installed capacity (kilowatts)	Average annual generation (1,000 kilowatt-hours)	Installed capacity (kilowatts)	Average annual generation (1,000 kilowatt-hours)	Installed capacity (kilowatts)	Average annual generation (1,000 kilowatt-hours)	
Androscoggin	31	138, 839	779, 000	370, 000	1, 214, 000	509, 000	1, 993, 000	27
Connecticut	120	510, 836	1, 830, 000	953, 000	2, 695, 000	1, 464, 000	4, 525, 000	35
Niagara	3	419, 487	3, 879, 000	1, 250, 000	7, 900, 000	1, 673, 000	11, 779, 000	25
Hudson	62	314, 711	1, 482, 000	351, 000	885, 000	666, 000	2, 367, 000	47
Susquehanna	26	628, 620	2, 914, 000	2, 124, 000	4, 588, 000	2, 753, 000	7, 502, 000	23
Potomac	21	18, 435	87, 000	772, 000	2, 331, 000	790, 000	2, 418, 000	2
Santee	58	845, 924	2, 377, 000	575, 000	1, 952, 000	1, 420, 000	4, 329, 000	60
Savannah	20	203, 457	566, 000	1, 061, 000	3, 257, 000	1, 264, 000	3, 823, 000	16
Alabama-Coosa	10	501, 177	2, 190, 000	2, 085, 000	9, 631, 000	2, 586, 000	11, 821, 000	19
Ohio (except Tennessee and Cumberland)	36	496, 129	1, 884, 000	5, 194, 000	22, 305, 000	5, 690, 000	24, 189, 000	9
Tennessee	46	2, 610, 072	13, 836, 000	813, 000	1, 955, 000	3, 423, 000	15, 791, 000	76
Cumberland	4	113, 820	600, 000	799, 000	2, 559, 000	913, 000	3, 159, 000	12
Colorado (Texas)	6	117, 020	399, 000	227, 000	535, 000	344, 000	934, 000	34
Red	8	156, 724	398, 000	803, 000	1, 874, 000	960, 000	2, 273, 000	16
Arkansas	10	85, 295	375, 000	1, 192, 000	4, 822, 000	1, 278, 000	5, 197, 000	7
White	4	87, 040	234, 000	1, 577, 000	3, 424, 000	1, 664, 000	3, 658, 000	5
Missouri	79	665, 094	3, 650, 000	8, 634, 000	40, 868, 000	9, 299, 000	44, 518, 000	7
Colorado	48	1, 328, 678	6, 898, 000	5, 733, 000	29, 014, 000	7, 062, 000	35, 912, 000	19
Sacramento-San Joaquin	77	2, 209, 490	12, 670, 000	5, 537, 000	27, 398, 000	7, 768, 000	40, 068, 000	29
Columbia	121	3, 208, 676	21, 370, 000	31, 239, 000	148, 229, 000	34, 448, 000	169, 599, 000	9
Totals:								
Listed basins		14, 659, 524	78, 418, 000	71, 289, 000	317, 436, 000	85, 947, 000	395, 854, 000	17
Unlisted basins		4, 007, 902	18, 489, 000	16, 315, 000	72, 379, 000	20, 324, 000	90, 868, 000	21
United States		18, 667, 426	96, 907, 000	87, 604, 000	389, 815, 000	106, 271, 000	486, 722, 000	18

TABLE 20.—*Estimated undeveloped water power in the United States, by geographic divisions and States, as of January 1951*

Division or State	Installation	Average annual generation
	Kilowatts	*Kilowatt-hours*
Continental United States	87, 604, 000	389, 815, 000, 000
New England	3, 250, 000	10, 240, 000, 000
Middle Atlantic	6, 572, 000	25, 555, 000, 000
East North Central	2, 344, 000	11, 090, 000, 000
West North Central	5, 775, 000	25, 164, 000, 000
South Atlantic	8, 151, 000	26, 114, 000, 000
East South Central	4, 736, 000	19, 818, 000, 000
West South Central	3, 568, 000	10, 333, 000, 000
Mountain	23, 440, 000	100, 313, 000, 000
Pacific	29, 768, 000	161, 188, 000, 000
New England:		
Maine	1, 611, 000	5, 684, 000, 000
New Hampshire	599, 000	1, 559, 000, 000
Vermont	625, 000	1, 585, 000, 000
Massachusetts	301, 000	918, 000, 000
Rhode Island	0	0
Connecticut	114, 000	494, 000, 000

TABLE 20.—*Estimated undeveloped water power in the United States, by geographic divisions and States, as of January 1951*—Continued

Division or State	Installation	Average annual generation
	Kilowatts	*Kilowatt-hours*
Middle Atlantic:		
New York	3, 051, 000	16, 903, 000, 000
New Jersey	225, 000	785, 000, 000
Pennsylvania	3, 296, 000	7, 867, 000, 000
East North Central:		
Ohio	212, 000	979, 000, 000
Indiana	323, 000	1, 151, 000, 000
Illinois	1, 111, 000	6, 271, 000, 000
Michigan	357, 000	1, 112, 000, 000
Wisconsin	341, 000	1, 577, 000, 000
West North Central:		
Minnesota	227, 000	1, 116, 000, 000
Iowa	414, 000	1, 895, 000, 000
Missouri	2, 472, 000	10, 775, 000, 000
North Dakota	652, 000	2, 543, 500, 000
South Dakota	1, 279, 000	4, 849, 000, 000
Nebraska	441, 000	2, 564, 000, 000
Kansas	290, 000	1, 422, 000, 000

TABLE 20.—*Estimated undeveloped water power in the United States, by geographic divisions and States, as of January 1951*—Continued

Division or State	Installation	Average annual generation
South Atlantic:	*Kilowatts*	*Kilowatt-hours*
Delaware	0	0
Maryland	382, 000	1, 007, 000, 000
District of Columbia	60, 000	221, 000, 000
Virginia	1, 371, 000	4, 487, 000, 000
West Virginia	2, 097, 000	7, 379, 000, 000
North Carolina	1, 169, 000	2, 881, 000, 000
South Carolina	940, 000	3, 315, 000, 000
Georgia	2, 042, 000	6, 498, 000, 000
Florida	90, 000	326, 000, 000
East South Central:		
Kentucky	1, 576, 000	7, 027, 000, 000
Tennessee	970, 000	2, 835, 000, 000
Alabama	1, 780, 000	8, 137, 000, 000
Mississippi	410, 000	1, 819, 000, 000
West South Central:		
Arkansas	1, 696, 000	4, 783, 900, 000
Louisiana	50, 000	200, 200, 000
Oklahoma	963, 000	3, 134, 910, 000
Texas	859, 000	2, 213, 500, 000
Mountain:		
Montana	6, 835, 000	25, 064, 000, 000
Idaho	8, 876, 000	37, 473, 000, 000
Wyoming	797, 000	3, 699, 000, 000
Colorado	1, 630, 000	8, 067, 000, 000
New Mexico	179, 000	880, 000, 000
Arizona	3, 701, 000	18, 900, 000, 000
Utah	1, 311, 000	6, 118, 000, 000
Nevada	111, 000	112, 000, 000
Pacific:		
Washington	15, 910, 000	87, 149, 000, 000
Oregon	6, 350, 000	34, 797, 000, 000
California	7, 508, 000	39, 242, 000, 000

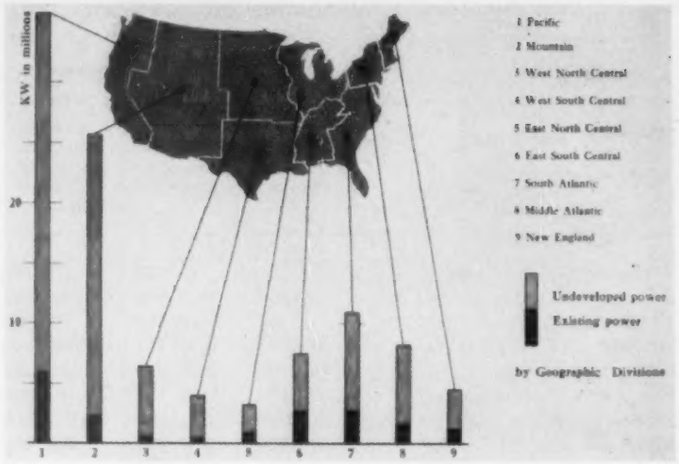


FIGURE 42.—*Existing and undeveloped hydroelectric power by geographic divisions.*

Total Hydroelectric Power in the United States by Geographic Divisions

Table 21 presents a summary of existing and undeveloped hydroelectric power in the United States by geographic divisions, as of January 1, 1951. The Pacific division has the largest aggregate existing development, totaling 5,979,821 kilowatts, or 32 percent of the United States total. In the eastern half of the United States, the South Atlantic division has the largest aggregate existing development, totaling 2,767,496 kilowatts, or about 15 percent of the total (fig. 42).

The Pacific division also exceeds the other geographic divisions in amount of undeveloped hydroelectric power, totaling 29,768,000 kilowatts, or 34 percent of the total for the United States. The Mountain division accounts for 23,440,000 kilowatts, or 27 percent of the total. In the eastern half of the United States, the South Atlantic division

TABLE 21.—*Existing and undeveloped hydroelectric power in the United States by geographic divisions, Jan. 1, 1951*

Divisions	Existing development		Undeveloped power		Total	
	Capacity	Average annual generation	Capacity	Average annual generation	Capacity	Average annual generation
	Kilowatts	*1,000 kilowatt-hours*	*Kilowatts*	*1,000 kilowatt-hours*	*Kilowatts*	*1,000 kilowatt-hours*
United States	18, 667, 426	96, 907, 000	87, 604, 000	389, 815, 000	106, 271, 000	486, 722, 000
New England	1, 230, 146	5, 033, 000	3, 250, 000	10, 240, 000	4, 480, 000	15, 273, 000
Middle Atlantic	1, 678, 025	9, 721, 000	6, 572, 000	25, 555, 000	8, 250, 000	35, 276, 000
East North Central	899, 596	4, 184, 000	2, 344, 000	11, 090, 000	3, 243, 000	15, 274, 000
West North Central	634, 862	2, 756, 000	5, 775, 000	25, 164, 000	6, 410, 000	27, 920, 000
South Atlantic	2, 767, 496	10, 644, 000	8, 151, 000	26, 114, 000	10, 918, 000	36, 758, 000
East South Central	2, 728, 758	14, 006, 000	4, 736, 000	19, 818, 000	7, 465, 000	33, 824, 000
West South Central	466, 129	1, 497, 000	3, 568, 000	10, 222, 000	4, 034, 000	11, 830, 000
Mountain	2, 282, 593	12, 550, 000	23, 440, 000	100, 313, 000	25, 723, 000	112, 863, 000
Pacific	5, 979, 821	36, 516, 000	29, 768, 000	161, 188, 000	35, 748, 000	197, 704, 000

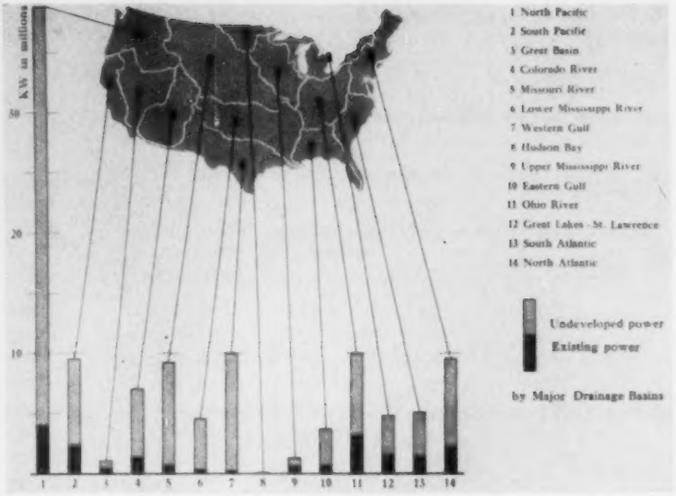


FIGURE 43.—*Existing and undeveloped hydroelectric power by major drainage basins.*

has the largest amount of undeveloped hydroelectric power, totaling 8,151,000 kilowatts, or about 9 percent of the total.

The major portion of the total possibilities for the development of hydroelectric power is in the Pacific and Mountain divisions, which together have about 61 percent of the country's total.

Hydroelectric Power by Drainage Divisions

Table 22 presents a summary of the existing and undeveloped hydroelectric power in the United States by major drainage basins as of January 1, 1951. The North Pacific drainage has the largest aggregate existing development with 3,872,374 kilowatts installed capacity. Taken together with the total of 2,289,540 kilowatts installed in the South Pacific drainage, the aggregate existing development on rivers draining into the Pacific Ocean is 6,161,914 kilowatts, or about one-third of the country's total (fig. 43).

The undeveloped power of the North Pacific drainage, which is comprised chiefly of the Columbia River Basin, is far in excess of other drainages, amounting to 34,945,000 kilowatts, or 40 percent of the United States total. The Missouri River drainage is second in amount of undeveloped hydroelectric power, with a total of 8,633,000 kilowatts capacity, or close to 10 percent of the country's total.

The combined existing and undeveloped power in the North Pacific drainage of 38,817,000 kilowatts is about 37 percent of the United States total. Next in amount is the Ohio River drainage with 10,018,000 kilowatts, or about 9.5 percent. The North Atlantic, South Pacific, and Missouri River drainages follow in order with 9,649,000, 9,514,000, and 9,298,000 kilowatts, respectively, each representing about 9 percent of the total.

Average Annual Runoff and Total Fall for Selected River Basins

Table 23 shows for selected river basins in the United States the average annual runoff from the drainage area above the lowest point on the river for which average annual runoff has been determined, and also the approximate total

TABLE 22.—*Existing and undeveloped hydroelectric power in the United States by major drainage basins. Jan. 1, 1951*

Drainages	Existing development		Undeveloped power		Total	
	Capacity	Average annual generation	Capacity	Average annual generation	Capacity	Average annual generation
	Kilowatts	*1,000 kilowatt-hours*	*Kilowatts*	*1,000 kilowatt-hours*	*Kilowatts*	*1,000 kilowatt-hours*
United States	18, 667, 426	96, 907, 000	87, 604, 000	389, 815, 000	106, 271, 000	486, 722, 000
North Atlantic	2, 202, 031	9, 469, 000	7, 447, 000	20, 478, 000	9, 649, 000	29, 947, 000
South Atlantic	1, 413, 059	4, 591, 000	3, 704, 000	11, 689, 000	5, 117, 000	16, 280, 000
Eastern Gulf	652, 691	2, 875, 000	3, 118, 000	12, 796, 000	3, 771, 000	15, 671, 000
Ohio River	3, 211, 421	16, 345, 000	6, 807, 000	26, 819, 000	10, 018, 000	43, 164, 000
Great Lakes-St. Lawrence	1, 531, 310	8, 999, 000	3, 312, 000	18, 155, 000	4, 843, 000	27, 154, 000
Hudson Bay	18, 107	80, 000	20, 000	91, 000	38, 000	171, 000
Upper Mississippi River	598, 892	2, 904, 000	746, 000	3, 416, 000	1, 345, 000	6, 320, 000
Missouri River	665, 094	3, 651, 000	8, 633, 000	40, 868, 000	9, 298, 000	44, 519, 000
Lower Mississippi River	320, 559	1, 009, 000	4, 339, 000	12, 801, 000	4, 660, 000	13, 810, 000
Western Gulf	199, 605	692, 000	899, 000	2, 979, 000	1, 099, 000	3, 671, 000
Colorado River	1, 323, 478	6, 898, 000	5, 738, 000	29, 014, 000	7, 062, 000	35, 912, 000
Great Basin	369, 265	1, 195, 000	671, 000	2, 876, 000	1, 040, 000	4, 071, 000
South Pacific	2, 289, 540	13, 104, 000	7, 225, 000	38, 049, 000	9, 514, 000	51, 153, 000
North Pacific	3, 872, 374	25, 095, 000	34, 945, 000	169, 784, 000	38, 817, 000	194, 879, 000

fall between the point and the highest existing or undeveloped hydroelectric plant in the basin. The total developed and undeveloped hydroelectric power in these basins is shown in table 19.

TABLE 23.—*Average annual runoff and maximum fall in selected river basins*

River basin	Point on river [1]	Drainage area above point (square mile)	Average annual runoff at point [2]			Maximum fall [3] in basin above point (feet)
			Number of years	Cubic feet per second	Thousand acre-feet	
Androscoggin	Auburn, Maine	3, 257	20	5, 709	4, 133	1, 670
Connecticut	Thompsonville, Conn	9, 661	21	[4] 16, 020	11, 600	1, 340
Niagara	Buffalo, N. Y	263, 500	44	[5] 193, 000	139, 732	[6] 326
Hudson	Mouth	13, 370	25	21, 500	15, 566	770
Susquehanna	do	27, 570	25	35, 800	25, 919	1, 150
Potomac	Washington, D. C	11, 560	18	[4] 10, 780	7, 805	1, 130
Santee	Pineville, S. C	14, 700	33	18, 460	13, 365	2, 010
Savannah	Clyo, Ga	9, 850	11	11, 530	8, 348	1, 840
Alabama-Coosa	Claiborne, Ala	22, 000	19	33, 580	24, 312	1, 450
Ohio (except Tennessee and Cumberland).	Mouth	145, 220	25	163, 500	118, 374	2, 600
Tennessee	do	40, 600	25	63, 700	46, 199	2, 240
Cumberland	do	18, 080	25	27, 800	20, 127	880
Colorado (Tex.)	Wharton, Tex	41, 150	16	3, 308	2, 395	1, 830
Red	Alexandria, La	65, 900	21	33, 240	24, 066	750
Arkansas	Little Rock, Ark	157, 933	22	43, 680	31, 624	9, 990
White	Newport, Ark	19, 812	16	24, 750	17, 920	920
Missouri	Herman, Mo	528, 200	25	70, 000	50, 680	8, 590
Colorado	Yuma, Ariz	242, 900	47	[7] 14, 800	10, 780	9, 670
Sacramento: San Joaquin	([8])	[9] 39, 600	40	45, 580	[10] 33, 000	6, 650
Columbia	Mouth	259, 000	69	248, 800	[11] 180, 100	6, 450

[1] Lowest point on river for which average annual runoff has been determined.
[2] From U. S. Geological Survey records, published or pending publication, except as noted.
[3] Approximate difference in elevation between point and highest existing or potential hydro plant in basin.
[4] Adjusted for diversions.
[5] Not including diversions from Lakes Michigan and Erie.
[6] Total fall in Niagara River.
[7] Actual flow. Long time average annual virgin flow of Colorado River at the International boundary estimated by Bureau of Reclamation to be 17,720,000 acre-feet.
[8] Points on tributaries of Sacramento and San Joaquin Rivers at entrance to valley.
[9] Approximate mountain and foothill area producing runoff into valley. Area of valley floor about 20,000 square miles.
[10] Bureau of Reclamation estimate.
[11] Corps of Engineers estimate.

Surface Reservoirs

MICHAEL STRAUS, *Commissioner, United States Bureau of Reclamation*

Historical Development

IT WOULD BE a rare occurrence for supply and demand on a stream system to balance over an appreciable length of time. Wide variations in discharge, with a few important exceptions, are characteristic of streams. Stream discharge varies from year to year, season to season, and day to day. Together with the variation in demand for water from a stream system, this results in either a surplus or a shortage in the immediate water supply.

Since irrigation in the West began with the development of land by diversion of water from relatively small streams, particularly those with annual floods from snowmelt, it soon became apparent that water supplies would be inadequate in the later part of the irrigation season for certain types of crops. Therefore, the usual type of irrigation development was based on crops that would mature early in the irrigation season and were largely made up of small grains and hay. Fortunately, this pattern conformed to the local demand and the economic development of the West at that time.

It was apparent in the early stages of irrigation development that, while the acreage of land was limited by the late season flow of water in the streams, there were periods of excess water. The capture and retention of this water until the season it was needed would permit the expansion of cropped areas. By this time, in the stage of irrigation progress, local economies had developed, and through changes in cropping patterns the demand for late-season water increased. Where capital was available, storage development began, usually in the form of off-channel reservoirs to be filled by diversion canals.

The off-channel reservoir was the result of local conditions. It could be constructed safely and economically, there being no fear of floods or high water; spillway costs were at a minimum, and the diversion canal could be constructed with tools, equipment, and methods available at that time. The disadvantages of off-channel reservoirs, the most important of which is lack of capacity, were not of great concern where irrigation developments were small. Where off-channel reservoirs could not be built either for lack of site or because of difficulty in construction of diversion canals to adequate capacities, main-stream storage was developed on smaller streams at the most economical sites.

This was about the situation in 1902 at the time of the passage of the National Reclamation Act. Local development had gone as far as it could, considering capital available and risks involved. The need, desirability, and economic return of irrigation had been demonstrated. There were known to be desirable projects that were ready for development, but their initiation was dependent on the availability of capital. This was supplied by the Federal Government.

Under the impetus of the Reclamation Act there began the development of what might be called the middle-sized stream systems such as the Salt River in Arizona, the North Platte River in Colorado and Nebraska, the Snake River in Idaho, the Rio Grande in New Mexico and Texas, and the Yakima in Washington. Irrigation projects increased in size but were yet simple in their operation. By 1930, however, plans had been made for the development of the larger stream systems. Economic development had proceeded to a point where power markets were of considerable importance. Thus, plans for the control of the larger streams, such as the Colorado, Columbia, and Sacramento Rivers, combined storage for irrigation with storage for power purposes. Since the demand for water for power production was not compatible with the demand for water for irrigation, means of reregulating stream flow had to be provided. The use of water was becoming more complex.

In the meantime local irrigation expansion was continuing. The phenomena of return flow from early irrigated areas provided a semiregulated supply of water for newer areas. Irrigation had increased the ground water supply and the development of efficient pumps increased the demand for water from this source. The result was that the demand for water in periods of drought began, in many areas, to exceed the water available. The highly developed local economies that had been based on irrigated areas were endangered and plans were made for the furnishing of supplemental water, usually in conjunction with the development on the larger stream systems (fig. 44).

The passage of the Flood Control Act of 1936 brought about a new consideration for the storage of water. Temporary storage of water during flood periods and its gradual release at later dates in many cases is an economic and effective means of flood control. The rapid expansion of Federal flood-control activities resulted in the planning and construction of many new reservoirs for flood control. However, in the arid and semiarid regions, flood-control storage has been added to, or combined with, conservation

storage, either for irrigation and power in the determination of the required reservoir capacity.

Thus, today we have arrived at the so-called multiple purpose project in which all phases of water control are given careful consideration. The use to which we are to put water has remained unchanged but the complexity of the irrigation system or systems within a river basin has increased manyfold.

Table 24 is based on the results of an inventory of reservoirs in the United States in excess of 5,000 acre-feet capacity made by the Geological Survey in 1947. According to the same survey, the earliest reservoir now in use constructed for irrigation storage was completed in California in 1859. However, most of the older reservoirs now in use in the Western States were completed in the last two decades of the Nineteenth century.

Capacity of Reservoirs

Reservoirs for irrigation storage can be divided roughly into two types, those providing seasonal storage or those providing cyclic storage. In the first type, storage is provided for the purpose of equalizing the flow of the stream during the year, while in the second, storage is provided to equalize the flow of the stream over a series of years. Seasonal storage reservoirs have a small capacity in relation to the annual runoff while those for cyclic storage have a large capacity in relation to the annual runoff of the stream and furthermore, a very large capacity in relation to the minimum annual discharge. Typical examples of these two types of reservoirs are shown in table 25.

The trend today is toward the building of cyclic storage reservoirs rather than the building of seasonal storage reser-

TABLE 25.—*Relation of storage capacity to annual runoff*

Reservoir	Capacity, acre-feet	Average annual runoff, acre-feet	Minimum annual runoff, acre-feet
CYCLIC STORAGE			
Roosevelt	1, 398, 000	728, 000	210, 600
Elephant Butte	2, 219, 000	1, 150, 000	178, 000
Lake Mead	27, 930, 000	12, 987, 000	4, 186, 000
Pathfinder	1, 040, 000	1, 258, 000	485, 400
SEASONAL STORAGE			
Arrowrock	286, 600	1, 900, 000	900, 000
Cle Elum	435, 700	646, 000	0
Buffalo Bill	456, 600	907, 200	536, 000
Gibson	105, 000	558, 000	302, 000
Pine View	44, 200	191, 900	27, 400

TABLE 24.—*Reservoirs in excess of 5,000 acre-feet capacity in the 17 Western States, Jan. 1, 1947*

State	All storage reservoirs		Irrigation storage reservoirs		Bureau of Reclamation storage reservoirs	
	Number	Capacity, acre-feet	Number	Capacity, acre-feet	Number	Capacity, acre-feet
Arizona [1]	16	35, 348, 000	13	35, 310, 000	9	33, 868, 500
California [2]	128	12, 745, 800	55	8, 675, 700	5	5, 641, 400
Colorado	79	2, 711, 600	72	1, 866, 300	4	400, 700
Idaho	42	5, 742, 200	41	5, 585, 200	11	2, 805, 600
Kansas	6	69, 500	1	30, 000	0	0
Montana	53	22, 653, 600	42	2, 604, 400	3	280, 600
Nebraska	8	2, 303, 600	5	2, 232, 900	3	103, 400
Nevada	7	645, 300	7	645, 300	2	473, 500
New Mexico	14	3, 138, 700	14	3, 138, 700	5	2, 349, 500
North Dakota	13	305, 300	0	0	0	0
Oklahoma [3]	22	9, 011, 500	1	151, 600	1	151, 600
Oregon	26	3, 414, 600	21	2, 539, 300	5	1, 399, 700
South Dakota	6	518, 000	2	211, 200	2	211, 200
Texas	43	6, 242, 000	13	4, 851, 100	1	[4] 1, 950, 000
Utah	28	2, 144, 400	28	2, 144, 400	8	697, 400
Washington	30	14, 062, 700	12	10, 736, 200	9	10, 699, 300
Wyoming	23	4, 023, 300	22	4, 015, 900	8	3, 803, 600
Total	544	125, 080, 100	349	84, 738, 200	76	64, 836, 000

[1] Includes Lake Mead, Ariz.-Nev.
[2] Includes Lake Tahoe, Calif.-Nev.
[3] Includes Lake Texhoma, Okla.-Tex.
[4] Marshal Ford (Lake Travis).

Source: Reservoirs in the United States, G. Earl Harbeck, Jr., U. S. Geological Survey Circular 23, March 1948.

voirs. This has been brought about from many reasons. The best and most obvious sites for seasonal storage reservoirs have been utilized. In many streams, new development is dependent on holding runoff during wet years that cannot be held in seasonal storage reservoirs. As development proceeds in a stream system only the more infrequent discharges are subject to capture and use, thus requiring reservoirs of large capacity. Also, present-day planning is looking toward basin development rather than project development and has resulted in the proposing of reservoirs for cyclic storage. Finally, the cost of storing an acre-foot of water usually varies inversely with the capacity of the reservoir.

However, it will never be possible to store all of the runoff that appears in years of high discharges for use in periods of deficiency. Water stored in surface reservoirs is subject to loss from evaporation. Any attempt to hold water in such reservoirs for too long a period fails for this reason. This is the major physical limitation on the maximum size of reservoirs needed to equate the discharge of a stream.

Cost of Reservoir Storage

While the general trend of the cost of storage of an acre-foot of water in a reservoir is upward, there is no clear-cut relationship. Between the years 1924 and 1941 the cost per acre-foot of storage in reservoirs of less than 200,000 acre-feet capacity ranged from about $2.25 to about $39.50, with an average of about $19. During the same period the cost per acre-foot of storage in reservoirs in excess of 1,000,000 acre-feet ranged from $1.50 to $14.50, with an average of about $5. Such reservoirs contained power developments, the cost of which is included in the unit cost of storage.

The cost per acre-foot of storage in reservoirs under construction at the present time ranges between $6 and $90. Certainly the upper limit of the cost of storage is higher today and is the result of many factors such as increase in cost of construction, poorer sites, and increase in the complexity of reservoir design to meet multipurpose use. It is not possible to isolate these factors and evaluate their individual effects, nor is it possible to evaluate the future cost of reservoir storage.

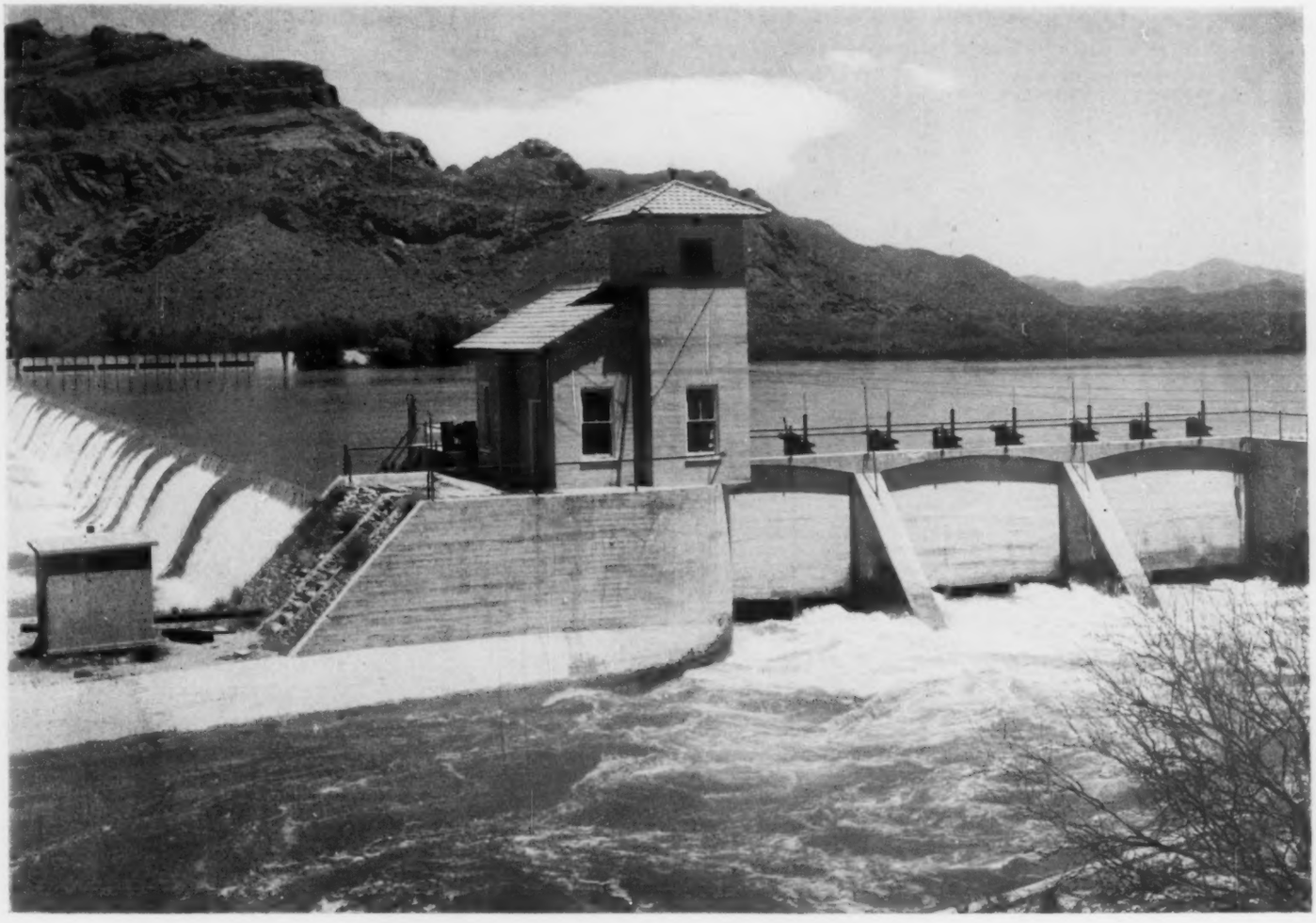


FIGURE 44.—*Granite reef diversion dam, Salt River project, Arizona.*

Potential Development

Of the streams draining large areas in the West, only two, the Gila River of Arizona and the Sevier River of Utah are fully developed. The San Joaquin Basin of California closely approaches full development. Full development has taken place on parts of stream systems such as the Platte, Arkansas, and Rio Grande, and the Great Salt Lake Basin. Here the development has been limited by the water supply. Such a limitation is absolute and can be lifted only by importation of water from other areas where surpluses are available.

On the other hand, it is now considered that the Missouri River Basin will be completely developed after the projects authorized in Senate Document 191, Seventy-ninth Congress, are completed. It can be stated that the limitations on development in this case are, in general, imposed by economic and physical conditions other than water supply. If in the Missouri River Basin there is duplicated the historical pattern of irrigation and power expansion observed in other areas, it can be expected that in some areas at least there will be future developments in the Missouri River Basin that cannot be foreseen at this time.

The development of the upper Colorado River Basin is only beginning. An apparent surplus of water in this area has resulted in a combination of within-basin development and the exportation of water to areas of deficiency on the periphery of the basin. Ultimate development is limited by economic conditions and availability of irrigable land, not water.

Much the same conditions exist in the Columbia River Basin and other river basins in the Northwest. A similar situation exists in stream basins in Texas and Oklahoma. Utilization of water in all these areas is in the initial stages and as long as there is a use for surplus water it may be expected that development will continue.

Inasmuch as stream flow cannot be fully utilized without some degree of regulation, future development must be dependent on reservoir storage. The magnitude of storage necessary can be realized when it is considered that the present plans for the control and full utilization of the waters of the Missouri River Basin include 138 reservoirs with a capacity of about 110,000,000 acre-feet, almost equal in capacity to all of the reservoirs for all purposes constructed up to 1947 in the 17 Western States. Control of the upper Colorado River, in order to fully utilize its water and yet meet the requirements of the Colorado River compacts, will require a total storage in excess of 40,000,000 acre-feet. It is doubtful that a reservoir system ever can be built to fully control the runoff of the Columbia River. The reservoir capacities required for such an undertaking would be enormous.

Techniques of Control

Water stored in reservoirs must be released at a time and in amounts to satisfy the demands of the user. If the reservoir is for power production, release will in part conform to load and will fluctuate from hour to hour. If the release is for irrigation, demand will have wide seasonal

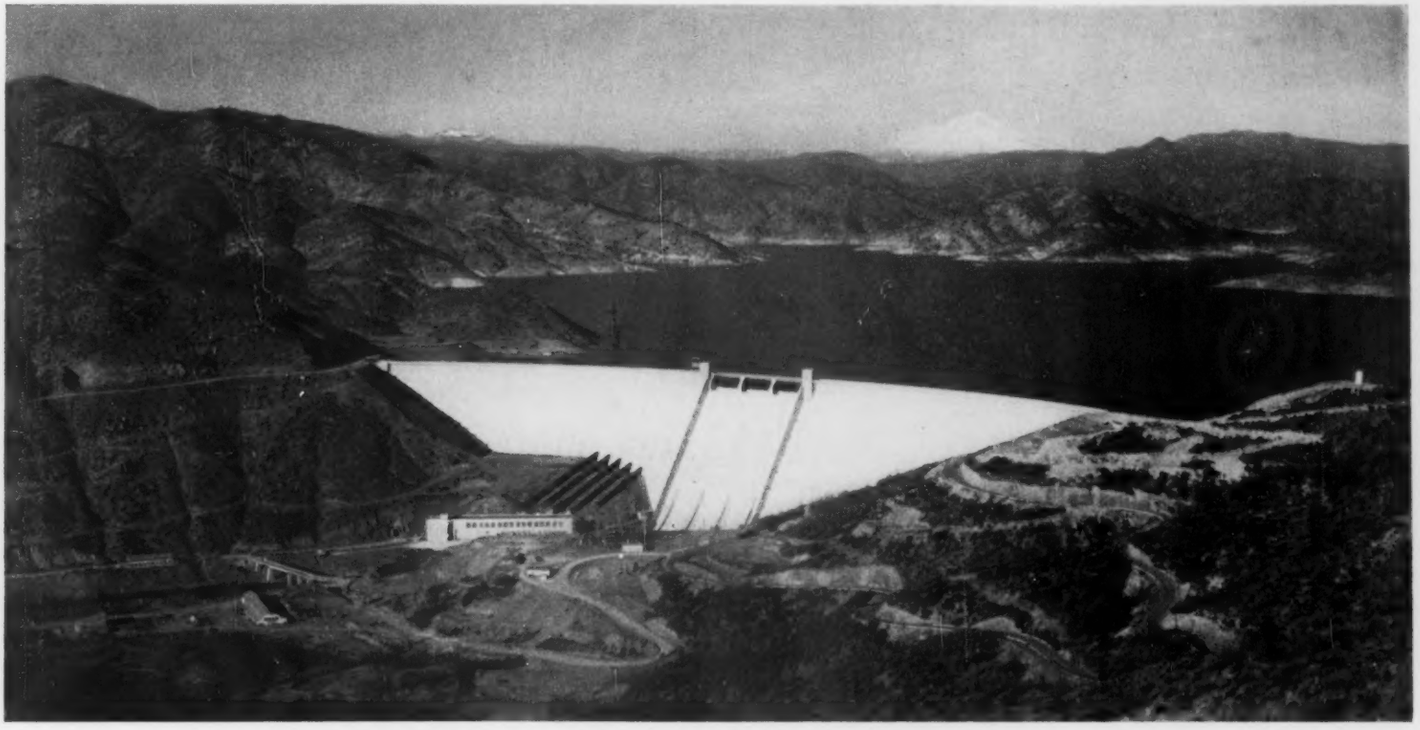


FIGURE 45.—*Shasta Reservoir and power plant, California.*

variations although releases may be relatively constant for periods within each season. Power releases, therefore, must be reregulated to insure full use of water for irrigation. Short period variation in reservoir release in streams that are subject to freezing is objectionable and must be controlled by reregulation.

Reservoir capacity to reregulate power releases is usually small. Nevertheless, pondage to provide reservoir capacity increases the area of water surface exposed to evaporation and may provide an increased opportunity for the growth of vegetation which will increase transpiration losses. The amount of water loss that can be attributed to reregulation is usually small in comparison to the total stream discharge. Nevertheless, even losses of small magnitude may be of considerable importance in some areas.

Water released from storage to be used for irrigation must be applied to the land. This is done by a system of canals, laterals, and ditches of various size, depending upon the area of the land to be served. Water may enter this system directly from the storage reservoir, but more commonly water from the reservoir passes downstream in the natural stream channel to a diversion dam where it is diverted into canals. In some irrigated areas there is a complex system of more than one diversion dam, the natural waterway being used to pass water downstream and to collect water wasted or unused on upper irrigated areas. Where such complex systems occur, water available in the stream system is divided among the various canals according to an established formula. The establishment of these formulas is the responsibility of the State, either in accordance with statute law or with court decree.

The moment water is stored in a reservoir it is subject to water loss; and upon its release from storage it is subject to further losses until it is finally utilized in crop growth. How to hold such losses to a minimum and yet meet the requirements of the irrigation demand is the principal problem of project operation. Since the pattern of distribution is fixed by crop and legal requirements, effective use of water must be approached by reducing losses.

There are two types of water losses: escape of water to the atmosphere through evaporation and transpiration, and movement of water out of the irrigation system through seepage, operational waste, or farm waste. The first type of loss cannot be recovered. Losses of the second type can be recovered in part, depending on how they finally influence losses from evaporation and transpiration. Water rarely escapes from a drainage basin by underground movement.

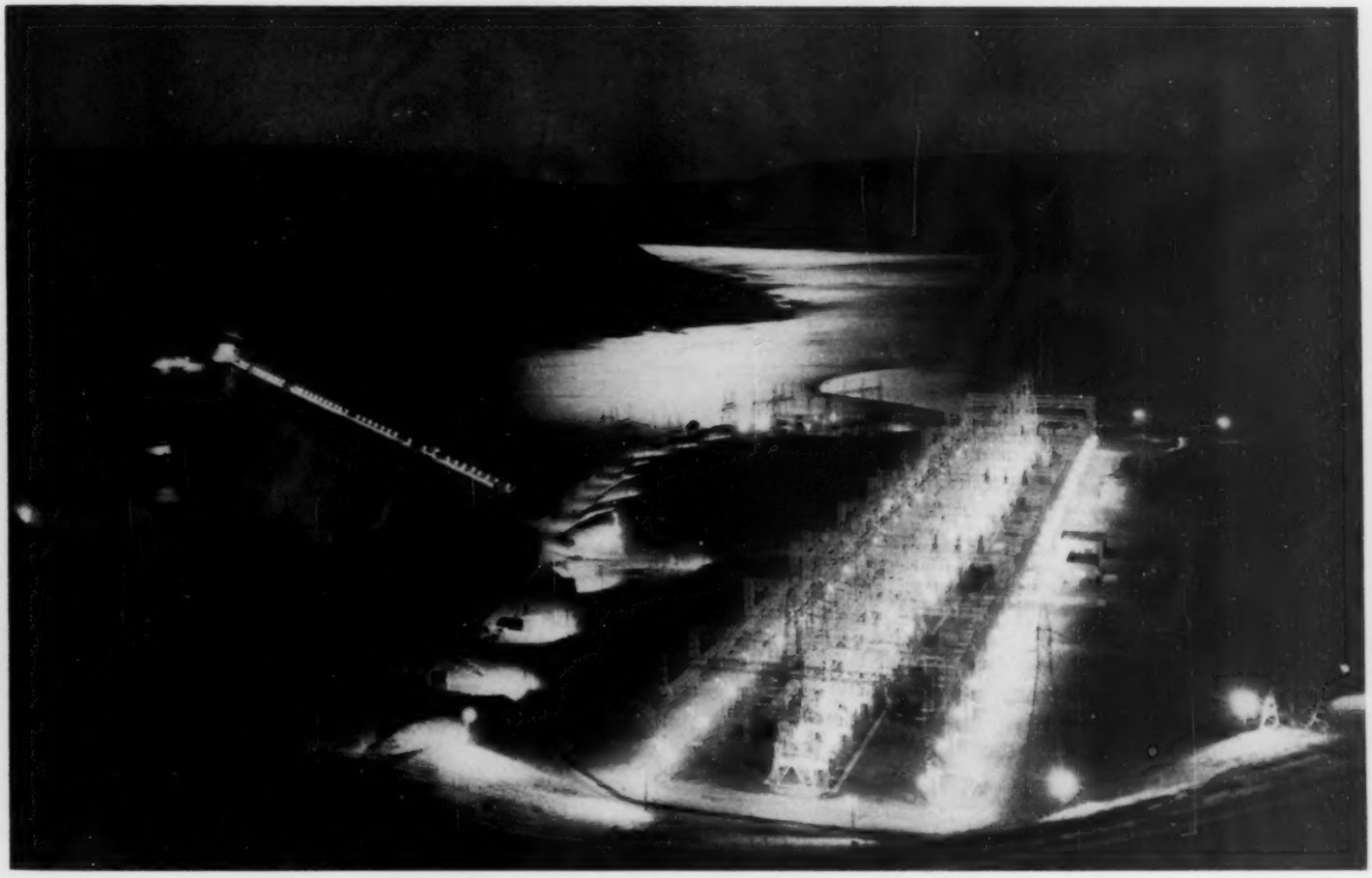


FIGURE 46.—*Grand Coulee Dam and Roosevelt Lake, Columbia River.*

The use of natural stream channels for the transmission of water has many advantages. There is no cost for preparing a channel. Seepage losses are low and advantage can be taken of natural inflows between the reservoir and point of diversion. However, evaporation losses from water surfaces of natural channels are usually higher than those from a canal of equivalent capacity and losses from transpiration by riparian vegetation may be high. It is rare when any work is done to reduce losses from natural streams. In general, cost is excessive and the amount of water to be saved is usually small. There are cases, however, in which channel deterioration through excessive deposition of sediment has resulted in a marked increase in evapotranspiration losses and where remedial programs can be undertaken. Examples are found in the Colorado River near Needles, Calif., the Pecos River near Artesia, N. Mex., and the Rio Grande near San Marcial, N. Mex. All three cases are complicated by deposition at the upper end of reservoirs and thus are not strictly examples of channel problems.

In the case of the Colorado River near Needles, Calif., the remedial program consists of dredging a channel through the swamped area to lower the water surface and narrow the channel. Because of the control of discharge and sediment afforded by Hoover and Davis Dams upstream from the area, it is expected that the program will be highly successful. In the cases of the Pecos River near Artesia, N. Mex., and the Rio Grande near San Marcial, N. Mex., relatively less control of discharge and sediment can be expected than on the Colorado River. Thus it is expected that remedial programs of channel construction in these areas will require relatively greater maintenance costs than will be found on the Colorado River.

Where canals and laterals are used for the transmission of water, losses take place from evaporation from the water surface, transpiration from riparian vegetation, and from seepage from the canal bed and banks. Evaporation losses from water surfaces cannot be avoided. Transpiration losses are reduced by removal of vegetation which is usually done in connection with normal cleaning operations to maintain canal capacity. Reduction in losses, therefore, is usually obtained by attacking the seepage problem.

The rate at which water escapes from a canal prism, all other things being equal, is dependent on the type of the material in which the canal is built. Seepage rates are high where such materials are fractured rock, gravelly, or contain large amounts of sand. They are low where the material is tight, as in clay. Recently constructed canals have higher

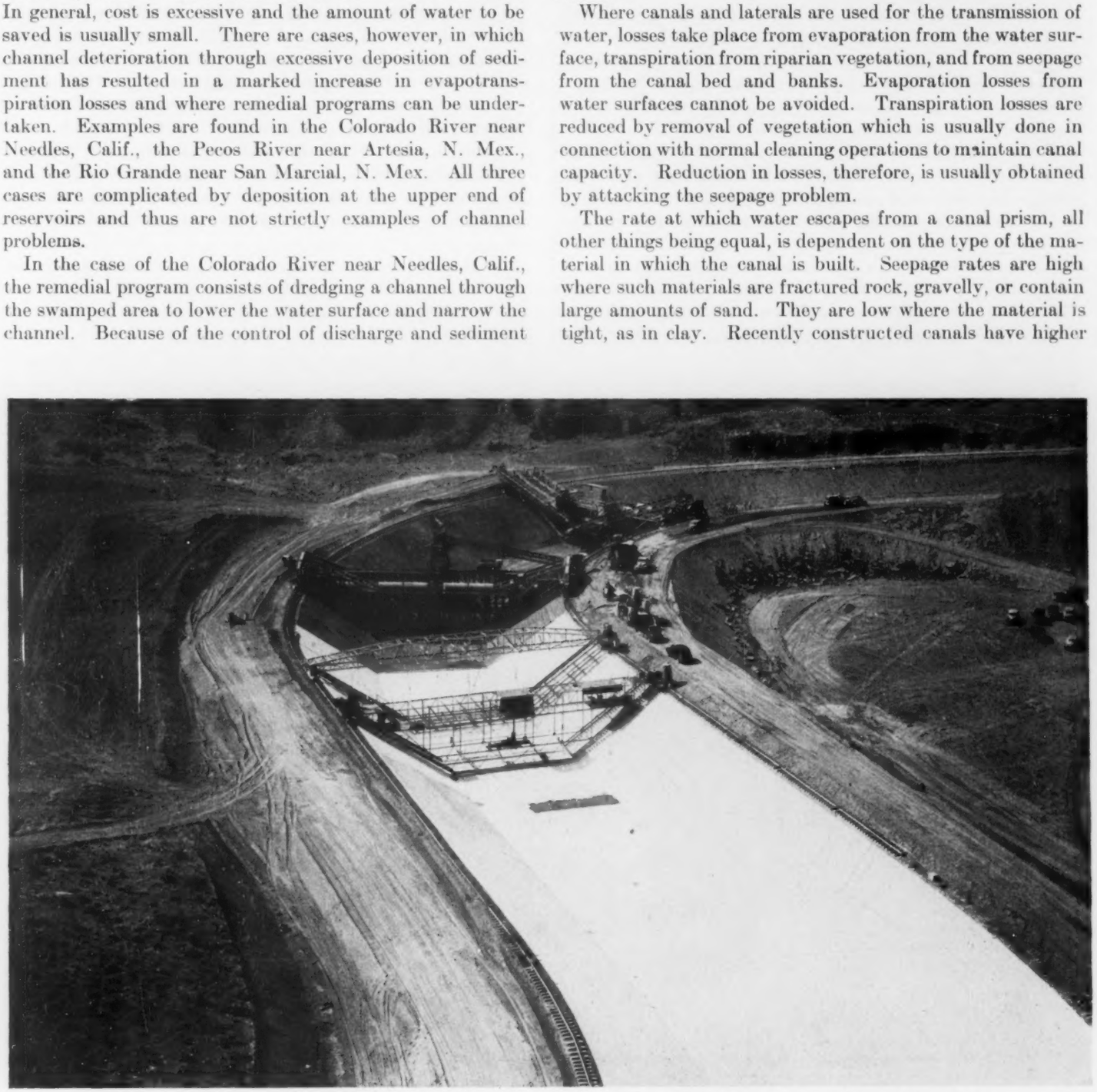


FIGURE 47.—*Canal lining machines (first machine, the curing jumbo; next, the trimmer; site, 4 miles west of Stratford, Wash.).*

seepage losses than old ones because water moving out of the prism carries with it some colloidal material which tends to seal the interstices of the original material. This sealing effect is, in some cases, broken by canal-cleaning operations so that after cleaning, canals lose more water than before.

Seepage losses are reduced by lining canals with an impervious material. This may be clay, asphaltic materials, or hydraulic-cement mixtures. The cost of various types varies widely but the greatest problem is to secure an effective lining at low cost (fig. 47).

Linings of lowest cost are those made of clay, asphaltic membranes, and soil-cement mixtures. Properly construed, all will reduce seepage losses. However, there is a considerable variation in the length of life of such linings. Linings of these types tend to be destroyed during canal-cleaning operations, and may be broken up by roots of vegetation growing along the banks. Where there is a wide variation in the depth of water flowing in the canal, these types of linings are subject to breakage from water pressures in saturated banks.

The Bureau of Reclamation has an active program of investigation of low-cost canal linings. In fiscal years 1950 and 1951, this program was financed by an allocation of one-third of 1 percent of all canal construction costs. Different types of low-cost lining are being installed and tested under field conditions of operation and maintenance.

Concrete canal linings are the most expensive type and rarely have been justified for water savings benefits alone. However, such linings, because they permit the use of higher velocities within the canal or the construction of a canal on a flatter slope, have other economic advantages which lead to their adoption.

Whether an attempt should be made to reduce seepage losses from a canal or lateral system is not easily decided in all cases. If seepage from canals or laterals is connected directly to the severity of a drainage problem or where seepage from canals is leading to an increase in consumptive use of water, there is little question to the consideration of benefits and costs. However, in many cases, seepage from canals is recovered by return flow from the irrigated area or by pumping. In such cases canal lining may save water by permitting a given supply to cover a greater acreage, but it may result in eventual diminution in the supply of water available at some other point. The effect of canal lining, therefore, must be carefully weighed in terms of its net result on water yield.

After water has been delivered to the farmer's head gate by the transmission system, losses still continue. If a farmer overirrigates, water may flow past his farm and not be recovered. Water may penetrate beyond the depth of plant roots and thus become unavailable to crops. Losses of this type are beyond the control of those in charge of the irrigation system and are the responsibility of the individual farmer. They tend to vary from year to year, being high when ample supplies of water are available, and low in years of water shortage when the farmer is careful to utilize his supply to the best advantage.

The only remedy for this type of waste is education. The Bureau of Reclamation, Department of Agriculture, and State agricultural colleges are engaged in educational programs aimed at better use of water by farmers. Results in this field have not been encouraging. Bulletins of the University of Arizona, published as early as 1905 called attention to these same bad irrigation practices.

It is perhaps unfair to say that little has been accomplished; nevertheless for over 40 years, the same methods for the proper utilizations of water on the farm have been known and recommended, but they are still largely ignored.

Sedimentation

Closely allied to the question of water losses in irrigation systems is the sedimentation problem. All streams carry sediment or debris to some degree. A very large portion of the sediment load of tributary streams is deposited in reservoirs and the water entering the canal system carries with it a certain portion of the sediment load of the river. This sediment load must either be carried to the irrigated land or removed from the irrigation system.

Sediment deposition in reservoirs decreases reservoir capacity—the diminution of storage capacity does not permit full regulation of the stream and results in loss of water over the spillways. Deposition of sediment in reservoirs usually increases the area of water exposed to the atmosphere for a given quantity of water in storage, thus increasing evaporation losses. Finally, sediment deposits are quickly invaded by water-consuming vegetation which increases transpiration losses from the reservoir area and for a distance upstream as well.

Reservoirs are usually designed to have a minimum length of unimpaired life by an allocation of a certain amount of their capacity to sediment storage. The practice of the Bureau of Reclamation is to provide for a minimum sediment storage allocation of 50 years, or the repayment period of the reservoir cost, whichever is greater. Estimates of the required space for sediment storage are based on an analysis of suspended sediment samples taken from the stream at or near the reservoir site or are estimated by comparison with data collected from other river basins. Measurements of sediment deposited in existing reservoirs are an important source of data in making such estimates.

Rates of sediment accumulation in reservoirs on rivers with large drainage basins vary from less than 0.10 acre-foot per square mile of drainage area to over 2 acre-feet per square mile of drainage area, and are dependent on the geology, topography, climate, vegetal cover, and condition of the drainage basin. Of these factors, only the vegetal cover and condition of the drainage basin are subject to change and manipulation. Within certain limits, therefore,

sediment loads can be affected by land management and this approach offers the best opportunity for some degree of control of sediment movement in streams. Unfortunately, available data applicable to the arid and semiarid regions are insufficient to properly evaluate the effect of land management in terms of costs and benefits resulting from reduction in sediment movement. Active prosecution of a program for the collection of such data would be of considerable benefit in the economic analysis of development programs for the West.

Sediment deposition in reservoirs can be modified to some extent by reservoir operation if provision is made in outlet design. The heavier and coarser fractions of the sediment load usually cannot be passed through a reservoir but the finer sizes, particularly those of the clay size, may be moved through the reservoir. Where such sizes make up a large fraction of the sediment load, this may be important. The principal requirements for moving sediment through a reservoir are very large outlet capacity and large amounts of water. Since water is rarely available for such a purpose, there are and will be very few reservoirs where sediment is evacuated from reservoirs as a means of maintaining capacity.

The movement of sediment into canal systems can be controlled to some extent by the design and location of intake works. Where sediment loads are high and where removal of sediment from the irrigation system would be a problem, desilting works may be provided at the head of the irrigation system. Such works may vary from a simple sedimentation basin to a complicated system of basins and mechanical clarifiers such as are found in the desilting works at the head of the All-American Canal on the Colorado River in California. In either case, the velocity of the water is reduced, thus causing the deposition of sediment. The deposited sediment is either flushed or pumped back into the stream system. In either case water used to remove sediment from a canal system represents an operational waste and may or may not be recoverable.

The cost of removal of sediment from canals is high. On the Shoshone project in northern Wyoming, 3.8 miles of the Deaver canal were cleaned in 1945, at a cost of about $1,020 per mile. On the Orland project in California, cleaning costs have been as high as $1,000 per mile in any one particular year. However, average annual costs are lower. Between 50 and 75 miles of laterals on the lower Yellowstone project in eastern Montana were cleaned each year during the years 1932–46 at an average cost of $75 per mile. The average cost of cleaning canals and laterals on the Orland project in 1946 was $178 per mile. Depending upon the size of the lateral and the variation of silt deposit, weeds, willows, tules and other vegetative growth, the annual cost of cleaning laterals varies from $50 to $150 per mile. Cost of removing sediment from the irrigation system of the San Carlos project of the Bureau of Indian Affairs amounts to about $1 per acre irrigated per year.

The sediment load carried by the irrigation system is one of the factors considered in canal design. The higher velocities permitted by the use of canal lining will carry heavier sediment loads. Costs of cleaning the lined Contra-Costa canal of the Central Valley project of California averaged $6.50 per mile. Other costs for cleaning lined canals range from $37 per mile to $50 per mile. Lesser maintenance costs coupled with other advantages derived from canal lining are of considerable influence in the decision to adopt canals of this type.

These costs are those chargeable to the operation and maintenance of a well-designed irrigation system where sediment problems are not severe. In many locations costs are considerably higher. In addition there are the unreported costs of the irrigation farmer who must clean his own field ditches and, from time to time, re-level his land so that it may be irrigated with a minimum of effort and with the best use of water.

A certain amount of sediment is desirable in a canal system. It tends to reduce the growth of aquatic vegetation, reduces seepage losses from canals, tends toward an increase in canal stability and may improve soil texture on cultivated land. Depending upon the type of sediment, it may or may not maintain soil fertility.

The Yuma irrigation project of Arizona and the Imperial irrigation project of California were both developed by using heavily sediment-laden water of the Colorado River. In both projects, cost of removing sediment from irrigation systems was high and in the case of the Imperial irrigation project amounted to over $700,000 annually. Regulation of the river by Hoover, Parker, and Imperial Dams, together with desilting works at the head of the canal systems provided water with practically no sediment load. The result was a very sharp drop in cost of removing sediment from the canal system but an increase in costs attributed to the removal of vegetation, decreased stability of canal sections, and increased seepage losses. Where originally the sediment load of the irrigation system had improved the texture of the sandy soil of the Yuma project, this no longer took place with the clear water available. The result was the abandonment of certain new lands proposed for irrigation because of very high water requirements.

Stopping of the sediment load of a stream by a reservoir results in scour or degradation below dams. This may lead to erosion of river banks formerly stable, undermining of bridge piers, reduction of river elevations below the level of pump intakes and other undesirable effects. Consumptive use of water depletes the discharge available to carry sediment and where sediment loads are returned to the stream from desilting works, may result in channel aggradation, an increase in drainage problems and river instability.

The sediment problem is inherent in any program of river development. This fact is now being realized to a greater extent than ever before but the solution to the problem is handicapped by lack of data and well developed or adequate techniques. Most Federal agencies concerned with river development have expanded their efforts in studying the sediment problem in all its phases. However, the problem is extremely complex and considerable time may elapse before it is fully understood.

Vapor Compression Distilling Plants

F. A. LOEBEL *and* J. M. STURMAN [1]

Introduction

A VAPOR compression distilling plant is a heat pump, designed for evaporating liquids. The features of this system are particularly advantageous for water distilling, although it has often been used with other fluids. Its main distinguishing feature is high fuel economy when compared with other types of evaporators, and when properly applied.

The story of vapor compression in this country is over 30 years old, but has found wide adoption and application only in the last 10 years, and is closely interwoven with the subject of water. Since the principle has been so widely documented, this paper will only briefly cover some of this history, and how vapor compression relates to our own experience. Some cost and power figures will also be given.

Vapor Compression Cycle

The idea of using a heat pump was suggested by Lord Kelvin in 1852, in a paper presenting a heating machine. A heat engine takes in a fluid at a given temperature and discharges it at a lower temperature, converting a small portion of the heat into work.

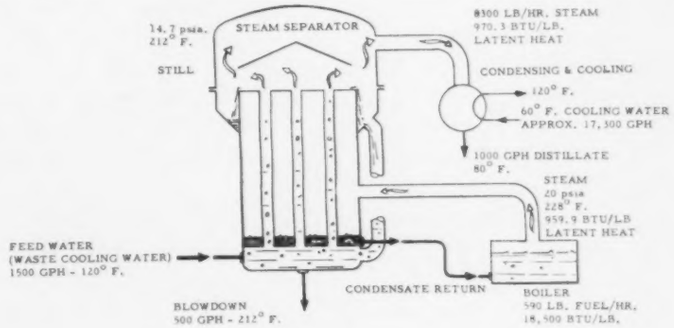
Kelvin's idea was to reverse this procedure and upgrade the temperature level of a gas or vapor by doing work on it, such as compression, thus taking in the gas at a lower temperature and discharging it at a higher temperature. This is the underlying principle of the vapor compression still.

Figures 48 and 49, which compare a 1,000 g. p. h. (gallons per hour) single effect, and a vapor compression plant, show the principal differences between the two methods. In the single effect it is necessary to supply all of the latent heat for vaporization, 970.3 B. t. u. (British thermal unit) for every pound of water evaporated, as well as the other losses, such as radiation, venting, etc. This total latent heat amounts to about 8 million B. t. u. per hour, and is almost completely lost in the waste cooling water. When added to other losses, the total heat supplied by the boiler fuel is 11 million B. t. u. per hour, or 590 pounds per hour of fuel, giving an economy of 14 pounds distillate per pound of fuel. This economy can be raised to about 25 by using a double effect. This is done by reusing the vapor boiled off in the first evaporator for generating an equivalent amount in the second evaporator. A triple effect would produce an economy of about 36, and so on. The maximum number of effects generally practicable for water is about 6. Note the large amount of cooling water required, about 17,300 g. p. h. This quantity is reduced to one-half for a double and to about one-third for a triple.

Referring to figure 49, it is seen that steam driven off in the evaporator is compressed by a steam compressor to a higher pressure and temperature so that it can be reused again for boiling off an equivalent amount in the same evaporator. Thus, the 8 million B. t. u. are continuously recaptured and recirculated within the system, and the only heat to be supplied is represented by the compressor load and the parasitic losses. With a Diesel drive, the auxiliary heat for starting up and maintaining the heat balance is supplied from the engine jacket.

History of Process

Historically, the idea is old. A patent covering a vapor compression evaporator was taken out by Pelletan in 1840,



HEAT BALANCE

OUT - BTU/HR.		IN - BTU/HR.	
1. Boiler Stack	2,225,000	1. Boiler Fuel	11,000,000
2. Blowdown 500 x 8.3 (212-32)	750,000	2. Feed Water 1500 x 8.3 (120-32)	1,100,000
3. Distillate 1000 x 8.3 (80-32)	400,000		
4. Cooling Water 17,300 x 8.3 (120-60)	8,650,000		
5. Radiation	50,000		
6. Venting	25,000		
Total	12,100,000	Total	12,100,000

FIGURE 48.—*Single effect water still.*

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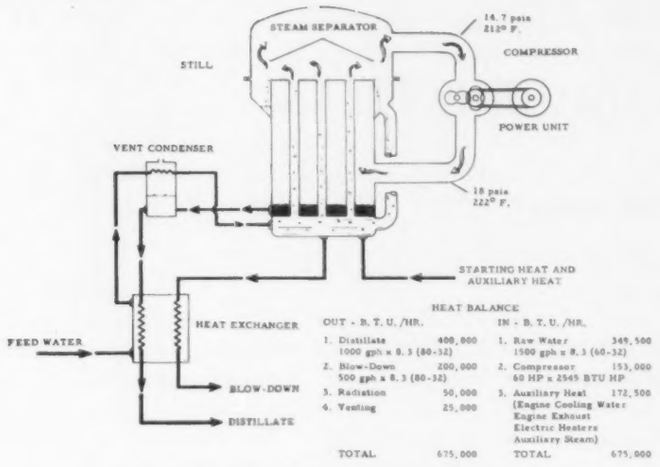

FIGURE 49.—*Vapor compression water still.*

even before Lord Kelvin presented his paper. Pelletan's machine utilized a steam jet compressor, but because of faulty nozzle design, was not a success. Nothing much was done until 1879, when the Piccard-Weibel system became quite popular. This machine used a reciprocating compressor and a few were installed in salt plants and sugar mills in France, Austria, and Switzerland. This system did not gain a foothold, however, probably because of deficiencies in the compressor, which was relatively large for a small output. The size of one model was 31.5″ bore x 19.5″ stroke. At 50 strokes per minute, and figuring it double acting, the evaporating capacity would be only 200 g. p. h. or 600 pounds of salt per hour. In 1943 one of these machines was reported to be still operating at the Salt Works at Bex, Switzerland.

About 1916, interest was again renewed by the Prache & Boullion concern in Paris, and they installed about 75 sets with steam jet compressors for various purposes, including the manufacture of tannin, glue, gelatin, and vegetable extracts. Even a crystallizing evaporator was built for salt production. In the Engineer magazine, in 1916, an economy of 100 pounds of water per pound of fuel is mentioned and also that an economy of 150 could be attained by using an internal combustion engine.

In 1918, a compression still was tested at Annapolis and reported in detail in a paper by M. C. Stuart, of the American Society of Naval Engineers. Economy obtained was about equal to a triple effect. William L. De Baufre, a mechanical engineer from the United States Naval Experimental Station, also did considerable work on vapor compression.

A considerable number of vapor compression machines were built in Switzerland for various purposes, starting about 1928. This development was not voluntary but rather was caused by a strong economic incentive—first, the high price of imported coal, and, secondly, the possibility of not having any during another war. The abundance of cheap hydroelectric power also favored the heat pump. The development fell naturally to three equipment manufacturers, Sulzer, Brown-Boveri, and Escher Wyss. At present, there is probably more total heat pump capacity in Switzerland than anywhere else in the world, if we neglect the thousands of compression stills built in this country for the military. Brown-Boveri have built 35 vapor compression plants, and Escher Wyss, 85, including the largest one in the world, which has a 220,000-pound-per-hour evaporating rate. Almost the entire salt requirement of Switzerland, some 80,000 tons per year, is produced by vapor compression without the use of fuel. The plant at Rybourg and Schweizerhalle each have a capacity of 40,000 tons per year.

An Escher Wyss vapor compression water distilling plant, utilizing a centrifugal compressor, was installed at Trail, British Columbia prior to 1938, with a capacity of about 2,000 g. p. h. The original plant is still running and another one has been added.

Although economic conditions in this country favor the compression, still in many cases, the economic compulsion was not nearly as acute as in Switzerland, and the need for this type of equipment here was brought about and hastened directly as a result of the war. The incentive was provided by the desperate need for water by our troops in the Pacific where, in places like Iwo, there was plenty of sea water, but no fresh water.

During the early war years, the Cleaver-Brooks Co. supplied most, if not all, of the portable land units. These were mainly packaged oil-fired double and triple effects. This was a natural outgrowth of our packaged boiler business. Since the problems in logistics called for maximum practicable fuel economy, we subsequently designed and built hundreds of the vapor compression type machines which largely superseded the conventional oil-fired types. With but few interruptions, we have carried on our manufacturing program on these machines, because of the continued demand.

Lower electric power rates and rising fuel prices have contributed toward sustaining this demand in no small measure.

Performance

Theoretically, the economy of a vapor compression plant can be carried to extremely high water to fuel ratios by using proportionately large evaporators and heat exchangers. Practically, the economy for Diesel plants is in the range of 200 pounds of distillate/pound fuel for small plants, up to 350 pounds of distillate/pound fuel for large plants.

Referring again to figure 49, the economy shown, 200 pounds distillate per pound of fuel, is conservative for large plants, since this economy requires a fuel rate of only 0.7 pound of fuel per b. hp. (boiler horsepower) per hour or 42 pounds per hour total fuel. Small Diesels, lightly loaded, would run this high, but large Diesels would be more in the order of 0.4 pound of fuel per b. hp. per hour providing an economy of 350, or equivalent to a 25 effect evaporator. Note that the cycle is self-sufficient regarding cooling water. The incoming feed is preheated by the outgoing blowdown and distillate, and no other cooling water is required.

All military models must pass an acceptance test of 720 hours of continuous operation on sea water without cleaning. The equipment lends itself readily to chemical cleaning, which can usually be accomplished in about 4 hours. Rigid standards of economy and water purity must also be maintained throughout the run. Typical performance data for a 720-hour run on sea water for a 1,000 g. p. h. compression still are shown in figure 50.

The drop in capacity as caused by scale formation on the evaporator tubes is also shown in figure 51. The sand stabilizer process for reducing sea-water scale, as developed by W. F. Langelier, D. H. Caldwell, and W. B. Lawrence in conjunction with the Army Engineer Board shows great promise. Operation of a Cleaver-Brooks 85 g. p. h. unit at Curaçao with a sand stabilizer is shown in figure 51. The evaporator pressure differential plotted along the vertical graph axis is almost a direct measure of the amount of scale formation. For comparison, the operation of an identical machine without sand stabilization is plotted which was run at Port Hueneme. Analyses of the Curaçao and Port Hueneme waters are almost identical.

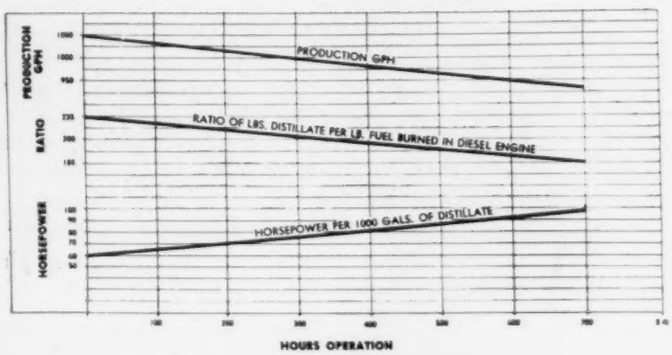

FIGURE 50.—*Typical performance curves.*

Applications

The applications encountered so far for compression stills have been mainly for distilling water of all types, ranging from water in the Persian Gulf area, with 45,000 p. p. m. total dissolved solids, to feed waters almost pure to begin with.

One of the most basic applications continues to be for military use—for land use because of high fuel economy, and for certain marine uses, because the still can be run with electric power only. Portability is also a factor, which is exemplified in a trailer-mounted, 85 g. p. h., Diesel-driven rig, weighing 5,000 pounds, shown in figure 52.

Vapor compression has proved to be highly attractive for pharmaceutical and industrial water distilling plants. Almost without exception, the power rates have been favorable enough to justify their adoption. Other advantages have also become apparent as evidenced by some installations, such as simplicity of operation as well as saving in

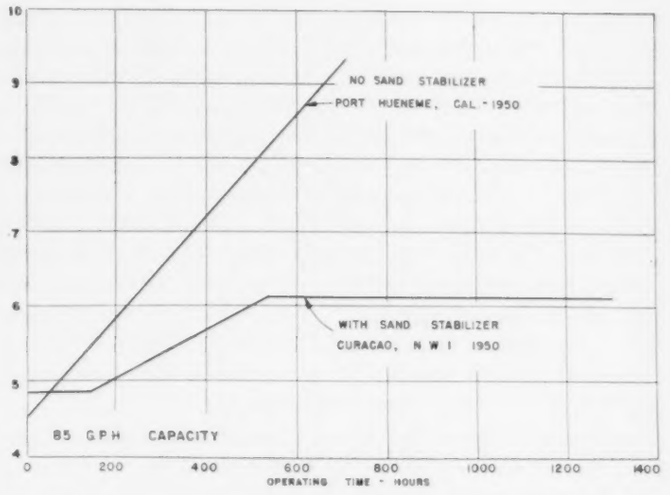

FIGURE 51.—*Sea water evaporator performance with sand stabilizer.*

considerable space. One such installation, which is believed to be the largest vapor compression plant in this country, is shown in figure 53.

There is little question, but that vapor compression plants will find many attractive applications in the concentrating field. At this time we have successful installations for concentrating amino acid and penicillin slurry. One of our plants has been operating for over a year on a special paper mill waste liquor. Extensive tests have also been made on black liquor, magnesium sulfite liquor, rum slops, and others.

Some commercial sea water distilling applications have taken us to far-off places—Arabia, Egypt, Southwest Africa, Venezuela, Eniwetok, Bermuda, the Bahamas, and Curaçao, to name a few. Curaçao is perhaps the most unique in that most of its water supply is distilled from the sea. It is probably the only place in the world where distilled water flows in domestic plumbing and is used for watering lawns and putting out fires. The water is presently distilled in sextuple effect Weir evaporators and is then generally blended with some well water high in solids. Scaling is a serious problem and about 15 men are continuously busy at chipping evap-

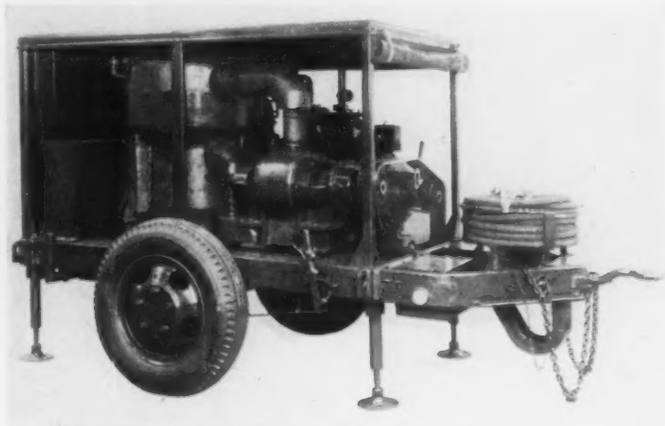

FIGURE 52.—*Portable sea water compression distilling plant.*

orator coils, since the equipment is not suitable for chemical cleaning. Water is also expensive; it is sold to domestic users by the Government at a loss for $4 for 1,000 gallons. Pure, unblended water is $6 per 1,000 gallons. These facts are merely brought out to indicate how water conditions can affect ones way of life. A fairly large household might spend $40 to $50 per month for water if they can afford it for lawn sprinkling, et cetera. Domestic users soon discover that there is a minimum flow where meters will not register, and allow their faucets to drip into pans at this rate all day long in order to collect water at no cost. In this tropical climate, workers in power plants and other industries nearly always arrive well ahead of time and leave late so that they can take showers on "company water."

In Bermuda, all of the water comes from rainfall. There are large catchments built on hillsides to catch rainfall, and also all housetops are constructed with calcimined coral slab shingles for collecting water in cisterns. A few goldfish are kept in each cistern to keep the water pure and sweet. Apparently these little fish do a good job; there has never been an epidemic due to faulty water in Bermuda, and the water really is quite palatable. The activities of the local health department consist of periodically checking the cisterns to see if the goldfish are still alive. If not, they are replaced.

Another use for compression distillation, which has received some little attention and which deserves a great deal more, is the furnishing of emergency supplies to areas whose water is polluted. For instance, if an atomic bomb were dropped in the water supply of a city, some means of purifying or decontaminating the water must be provided immediately. It has been determined that radioactive water can be decontaminated by distillation. It follows that vapor compression is one of the most favorable methods of accomplishing this. Figure 55 shows a photograph of a small pilot plant being tested for this purpose by the Brookhaven National Laboratories.

It has been proposed that portable machines of large capacity, say 10,000 gallons per hour, which can be transported on flat cars, be constructed and held in strategic locations. In sufficient numbers, these machines could provide emergency water supplies in the event of atomic bombing of metropolitan centers.

In this country a great deal of attention has geen directed toward a method of producing fresh water from sea water for municipal use. This was particularly true 2 years ago when there was an acute water shortage in southern California due to the prolonged drought. Several methods of transposing sea water to fresh water have been advanced, many of which are impracticable. During World War II small chemical kits were furnished in life rafts for removing the minerals from sea water to provide a couple of quarts of drinking water. It will be shown later that this principle cannot be applied economically on a large scale.

Some of the methods which have been proposed are electrolytic demineralization; production of condensate and power by means of the thermal difference power plant, or Claude process; evaporation by means of waste heat from Diesel plants, or steam power plants; producing ice crystals of fresh water from sea water, reclamation of sewage; and others. Some of these methods, particularly the ones proposing evaporation by waste heat sources, appear attractive. To date, however, studies concerning the economies of the alternate methods are not yet conclusive. The only method that has been reduced to practice on a large enough scale is distillation.

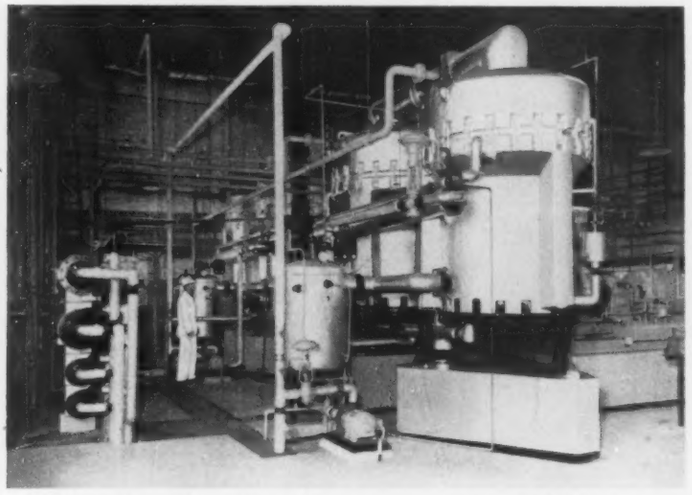

FIGURE 53.—*Motor driven water vapor compression distilling plant.*

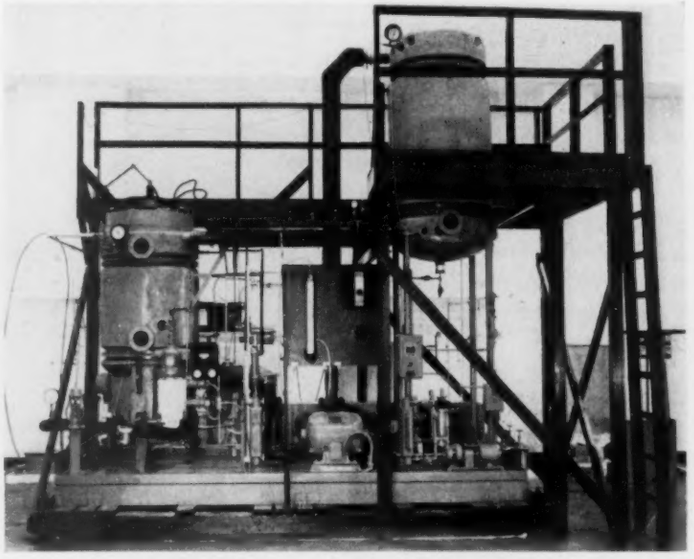

FIGURE 54.—*Experimental vapor compressor for distilling radioactive wastes.*

Cost of Distillation

Table 26 has been prepared showing the cost of steam distillation versus compression distillation. The cost of demineralization by chemical means is also included as a matter of interest.

The most economical means shown, a compression distillation plant powered by electric motors, produces water for a total cost of $1.12 per thousand gallons. Of this, the electric power represents only 18 cents, the amortization 38 cents, and charges for operating personnel 35 cents.

It is possible that the total cost of water by vapor compression can be markedly reduced through lower capital cost as a result of advanced technology.

If an evaporator plant could be tied in with an existing power plant or waste heat sources in the locality needing water, thereby obtaining free fuel, steam distillation would likely be even cheaper than compression distillation.

It is of particular interest, from table 26, that the capita cost of a triple effect steam still, including the steam generating plant, is approximately equal to the cost of a vapor compression distilling plant. Although the heat transfer surface of the triple effect is smaller than for a vapor compression plant due to the greater temperature difference, the costs of auxiliaries and boiler plant raise its total cost to equal vapor compression.

Considering possible improvements in methods and construction, the lowest estimated cost now by compression distillation would be about 60 cents. To compare with this figure, the municipal water suppliers of the 400 larger cities of the United States charge industrial users an average of 12 cents per thousand gallons. Many smaller communities charge domestic users as high as 35 to 40 cents per thousand gallons. From this then it would appear that compression distillation for smaller communities could compete with natural water sources and almost certainly could be justified for emergency use. In our own experience we have noted that many communities along the sea shore and distant from natural water supplies can obtain fresh water by compression distillation more cheaply than they can run long pipe lines.

Conclusions

Compression distillation as presently manufactured and at its present costs for plant and operation is the most economical proven means of providing distilled water from sea water; it is usually the most economical method of evaporating water from weak chemical solutions; it is likely to be the best and in many cases the only means of providing fresh water in arid and isolated sections along coastlines; and finally, and of grave importance right now, it is the only proven and practical way to furnish emergency water supplies to communities which have been attacked with atomic bombs.

TABLE 26.—*Comparison of costs per 1,000 gallons for producing fresh water from sea water by various methods based on a plant for 10,000 gallons per hour*

	Chemical demineralization	Steam distillation			Compression distillation	
		Single effect	Double effect	Triple effect	Diesel engine plant	*Electric motor plant
Plant cost, erected without buildings (non-ferrous construction)	$8,000,000.00	$375,000.00	$390,000.00	$425,000.00	$500,000.00	$450,000.00
Amortization, basis 15 years	6.66	.31	.33	.42	.42	.38
Steam cost, based on fuel, at $0.06 per gallon		5.02	2.61	1.71	None	.14
Diesel fuel cost, based on fuel, at $0.07 per gallon					.28	
Electric power cost, based on power, at $0.003 per kilowatt	.01	.10	.08	.07	.01	.18
Cooling water cost, at $0.12 per 1,000 gallons		2.40	1.20	.80	None	None
Lubricating oil, at $0.70 per gallon					.04	.01
Descaling heat transfer surfaces		.02	.02	.02	.02	.02
Maintenance and repair	.04	.04	.04	.04	.09	.04
Operating personnel and supervision	.17	.35	.35	.35	.35	.35
Chemicals for regeneration	25.00					
Total cost	31.88	8.24	4.63	3.34	1.21	1.12

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Reclamation of Water From Sewage and Industrial Wastes

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Introduction

THE RELATIONSHIP between water supply and population, agriculture, and industry that an area can support is of fundamental significance. For example, as southern California has grown from the early pueblo days to its present metropolitan status, so has its source of water supply changed from the once-flowing Los Angeles River to a system which includes extensive development of local ground waters and importations from the Sierra Nevada Mountains and the Colorado River.

The present outlook is favorable for future rapid population growth in southern California. Engineering planning must cope with the new water problems which are bound to accompany this great expansion. There is need for an over-all water plan to include within its scope all possible supplies of acceptable water; i. e., local supplies including conservation of floodwaters, imported supplies, sea water, and water reclaimed from waste or spent waters. Only from such a thorough study can a true picture be drawn and each source compared with the others on the basis of feasibility and economics.

A report for southern California has been prepared as a collection and review of data relating to one possible source of water supply; i. e., the reclamation of water from sewage and industrial wastes.

While this is but one phase of an over-all water plan, it is recognized that in water reclamation from sewage and industrial wastes there is an immediate source of raw-water supply already available to the area. Factors that may retard the advance of such reclamation include public prejudice toward the use of water reclaimed from sewage, lack of proper health and nuisance standards, and the absence of clear legal authority to proceed with an operational program. The scientific and engineering principles necessary to reclaim from sewage a water suitable for any useful purposes are already well founded.

Water-Reclamation Processes

The use of sewage and industrial wastes as a source of useful water has been practiced for centuries. Sewage farming, in fact, was the first method of sewage disposal, and until fairly recent times was the only process so recognized. These early sewage farms were irrigated with raw sewage. As the trend toward emphasis of public health and control of nuisances has developed, so the trend in sewage treatment has of necessity followed.

A properly designed sewage-treatment plant of today can, and many do, produce a well-oxidized, clear, sparkling, and sterilized effluent which is of better quality chemically and biologically than many public raw-water supplies. The value of such effluents is readily seen, and more attention has been given to their further utilization in agriculture, industry, and recreation, and for supplementing ground water supplies.

That reclamation and reuse of water from sewage is an accomplished fact is attested by many small sewage-treatment plants all over the West, and by thousands upon thousands of cesspools and individual septic tanks from which water leaches into the underground strata to be reused for domestic, agricultural, and industrial purposes.

While it is recognized that water is so reclaimed and rendered available for reuse, it occurs only infrequently that a sewage-treatment plant is intentionally planned to supplement or augment a water supply. It is generally the case that recovery of an acceptable effluent from a sewage-treatment works is incidental to a necessary or imposed sewage-treatment process and seldom the primary factor influencing the plant design (fig. 55).

A review of the sewage-reclamation situation was recently presented in the form of a symposium to the Federation of Sewage Works Associations, and in this review the authors mention but three small sewage-treatment works designed and operated more particularly for the recovery of water for reuse than because conditions imposed the process for the disposal of the sewage itself. These were at Harrington, Kans., the Grand Canyon of the Colorado, and Golden Gate Park, San Francisco. Each of these plants is designed to produce reusable water which is better for the purpose intended, or more economical, or both, than is otherwise available in the area.

These facts were known in advance of planning and construction and were the considerations which influenced the design. In practically every other instance noted where

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sewage is used for irrigation, industry, or otherwise, it is merely a step incidental to sewage disposal, the recovery of sewage effluent from a flowing stream, or, as is particularly the case at Baltimore, an extension by industry of the purification processes otherwise imposed upon a municipality at its sewage-treatment plant.

At first thought, it may seem that water reclamation should, for reasons of economy, be a corollary of sewage treatment. A few additions to the normal sewage-treatment-plant design are all that may be believed necessary to expand the usual sewage-treatment operation into one of water reclamation. While this is true from the standpoint of engineering and sanitary chemistry, a careful investigation of the entire matter sheds an entirely different light upon the issue. In fact, the one thing that will unlock the door to safe and acceptable water reclamation from sewage is its complete separation from sewage disposal, to be considered as an independent operation by itself (fig. 56).

There are some very significant differences between the processes of sewage disposal and water reclamation. The function of a sewage-treatment plant is to process all of the sewage which reaches it at any time. To produce a well-oxidized and purified effluent, the plant features must include all of those which will successfully dispose of all sewage solids retained at the plant as well as those features required to oxidize and perhaps sterilize the sewage effluent. More significantly, the plant must process all of the sewage flow as and when it arrives, regardless of its composition, temperature, strength, or any other features which render it difficult to treat.

In contrast, a water-reclamation plant using domestic sewage and/or industrial water as its raw water supply and not, in any sense, a part of the sewerage system, would not be forced to operate at times when operation was inadvisable, or with sewage of such character as to render the process ineffective. Neither would it be necessary for the plant to take the sewage quantitatively as it comes or to retain in the plant any sewage or mixed sewage and sludge detrimental, or not beneficial, to the reclamation process. Furthermore, the plant would not be plagued by the necessity of disposing the solids removed from the sewage. These could be emptied back into the sewerage system for disposal elsewhere.

While the economics of design of the water-reclamation plant might indicate that it should have a definite capacity, however, the plant would never operate on amounts beyond its capacity to do a satisfactory job.

This comparison emphasizes the value of an already completed and satisfactory sewerage system, including sewage disposal, in advancing the possibilities of water reclamation.

Need for New Standards

Because so many of the objectionable and pressing features in sewage-treatment-plant construction and operation would be absent from such a water-reclamation plant, there is need for a reevaluation of the public-health factors, esthetics, and the economics of water reclamation in this new light.

It would appear that the significant differences between the two operations pointed out above will have to be recog-

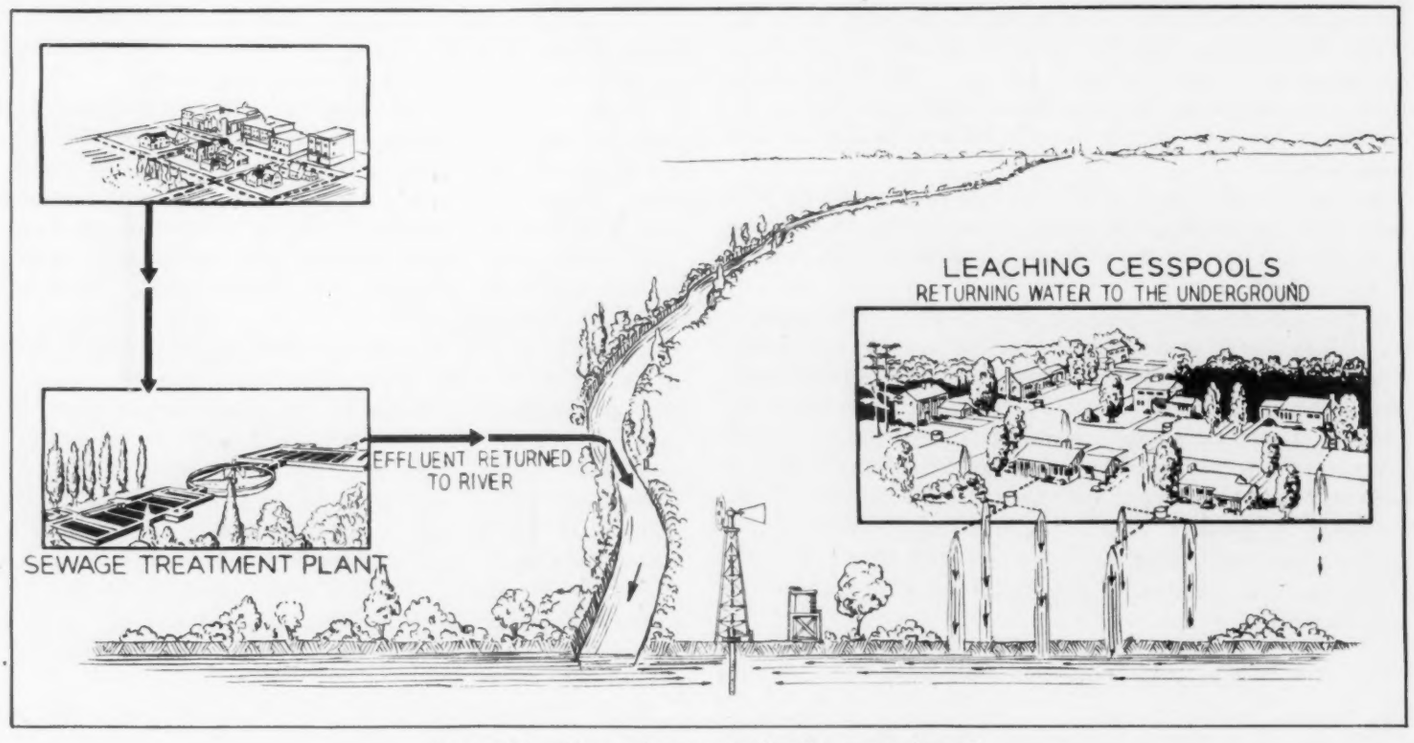

FIGURE 55.—*Water reclamation incidental to sewage disposal.*

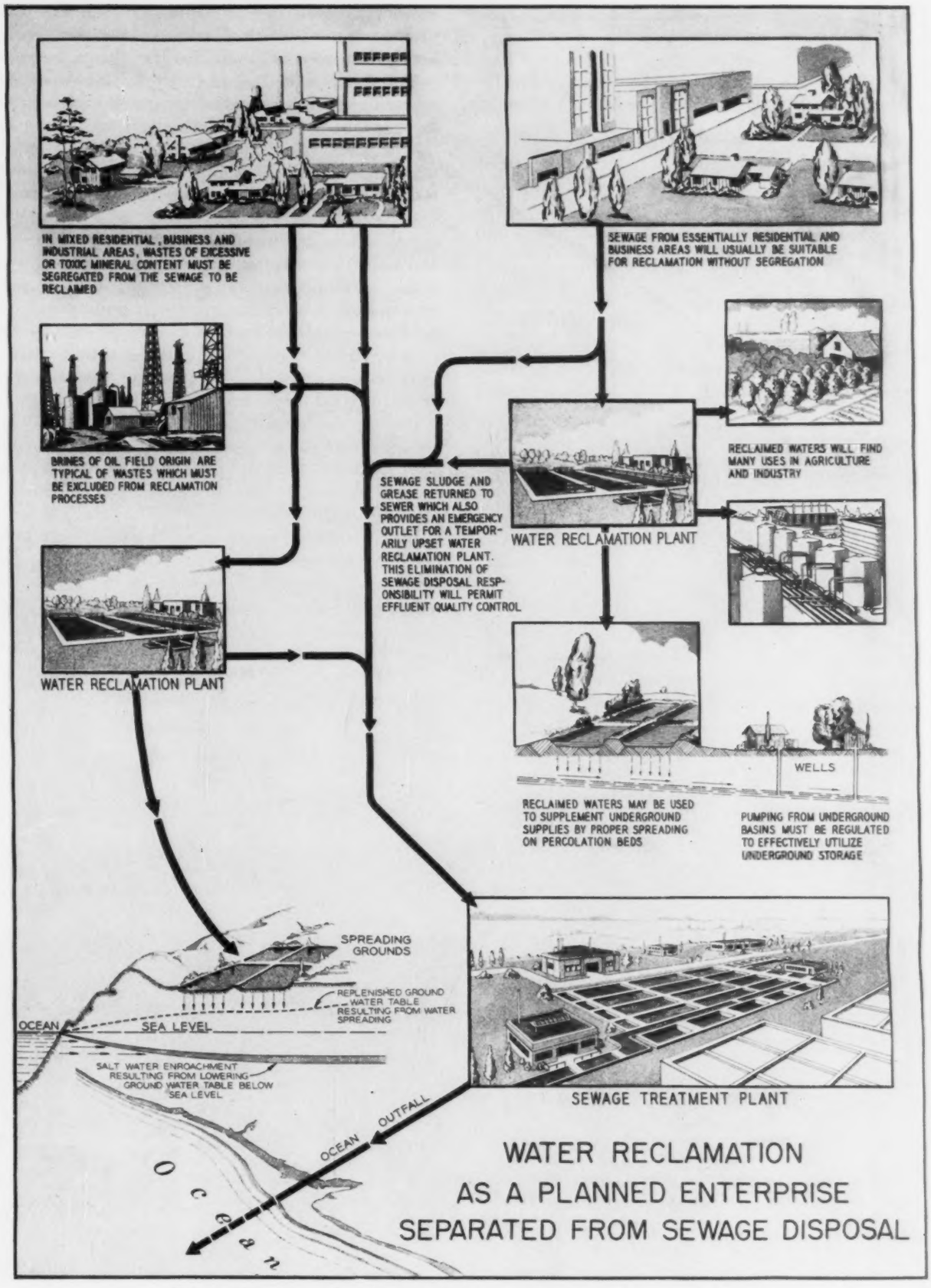
IN MIXED RESIDENTIAL, BUSINESS AND INDUSTRIAL AREAS, WASTES OF EXCESSIVE OR TOXIC MINERAL CONTENT MUST BE SEGREGATED FROM THE SEWAGE TO BE RECLAIMED
SEWAGE FROM ESSENTIALLY RESIDENTIAL AND BUSINESS AREAS WILL USUALLY BE SUITABLE FOR RECLAMATION WITHOUT SEGREGATION
BRINES OF OIL FIELD ORIGIN ARE TYPICAL OF WASTES WHICH MUST BE EXCLUDED FROM RECLAMATION PROCESSES
SEWAGE SLUDGE AND GREASE RETURNED TO SEWER WHICH ALSO PROVIDES AN EMERGENCY OUTLET FOR A TEMPORARILY UPSET WATER RECLAMATION PLANT. THIS ELIMINATION OF SEWAGE DISPOSAL RESPONSIBILITY WILL PERMIT EFFLUENT QUALITY CONTROL
WATER RECLAMATION PLANT
RECLAIMED WATERS WILL FIND MANY USES IN AGRICULTURE AND INDUSTRY
WATER RECLAMATION PLANT
WELLS
RECLAIMED WATERS MAY BE USED TO SUPPLEMENT UNDERGROUND SUPPLIES BY PROPER SPREADING ON PERCOLATION BEDS
PUMPING FROM UNDERGROUND BASINS MUST BE REGULATED TO EFFECTIVELY UTILIZE UNDERGROUND STORAGE
SPREADING GROUNDS
REPLENISHED GROUND WATER TABLE RESULTING FROM WATER SPREADING
OCEAN
SEA LEVEL
SALT WATER ENROACHMENT RESULTING FROM LOWERING GROUND WATER TABLE BELOW SEA LEVEL
OCEAN OUTFALL
Ocean
SEWAGE TREATMENT PLANT
WATER RECLAMATION
AS A PLANNED ENTERPRISE
SEPARATED FROM SEWAGE DISPOSAL

FIGURE 56.—*Water reclamation as a planned enterprise separate from sewage disposal.*

nized by the health authorities if water reclamation is to be established on a firm and just basis.

Characteristics of Sewage and Industrial Wastes

Sewage contains mineral, animal, and vegetable matter in suspension and solution, together with a large number of bacteria. The materials in suspension consist of fecal matter, paper, grease, pieces of food, etc. However, the concentration of organic and mineral solids is very small, amounting to about 0.1 percent (1,000 p. p. m.). In other words, sewage is about 99.9 percent water. The nature and quantity of the organic portion of sewage (both suspended and dissolved) is of utmost importance, for it is this small fraction which gives rise to its offensive characteristics. Sewage-treatment processes attempt to remove a part (partial treatment) or all (complete treatment) of this offensive organic matter.

The above-noted sewage characteristics are directly influenced by (1) the nature of the water supply or supplies in use, (2) the habits and contributions of the people in the tributary area, (3) the presence and nature of institutions and industries, and (4) the amount of infiltration into sewers from ground or sea waters.

Quality of Water Reclaimed From Wastes

The quality of present-day sewage-treatment-plant effluents is a function of the means of effluent disposal employed and consequently varies widely. Where satisfactory ocean effluent disposal is obtainable (as with the Los Angeles County Sanitation District's ocean outfall), only primary sewage treatment is deemed necessary prior to ocean disposal.

The function of the modern complete sewage-treatment operation is to process the sewage in such a manner as to separate out its water content and discharge the latter from the plant as a stable, sterile water altered only from the original water by a change in its stable mineral content. Each of the putrescible organic materials of sewage origin—i. e., proteins, carbohydrates, and fats (containing the elements carbon, hydrogen, oxygen, and in some cases nitrogen and sulfur)—is decomposed and transformed into compounds stable in composition and with inoffensive properties. This decomposition occurring with an ample supply of oxygen results in stable end products such as carbon dioxide, nitrates, nitrites, and sulfates. In this manner, the suspended solid content and biochemical oxygen demanding substances of the original waste material are practically eliminated

It must be clearly understood that, even though the sewage-treatment plant eliminates these putrescible materials and produces a stable and easily disposable effluent, the process is not intended to remove inorganic dissolved materials such as chlorides, sulfates and bicarbonates of sodium, calcium, magnesium, and compounds containing boron and other such substances. These materials pass through the normal sedmentation and biological process unchanged and appear in an undiminished concentration in the plant effluent. Furthermore, it is not possible to remove these inorganic materials by any ordinary modification of these processes.

A water-softening process following so-called "complete

FIGURE 57.—*Rio Hondo spreading grounds (cultivated and ready for water).*

treatment" would remove the substances causing hardness (calcium and magnesium). However, the extra expense involved would probably preclude such a practice.

From the standpoint of practicality, then, the quality of the effluent produced from any sewage and industrial waste will depend greatly upon the relative amounts of dissolved minerals initially present in the sewage and industrial waste.

The problem of segregation of harmful and useful wastes to control the quality of reclaimed effluents will be much easier with this initial progress already accomplished. Restrictions must be more inclusive, however, if the reclamation plan is to be developed Other waste materials not objectionable from the disposal viewpoint will seriously impair the quality of reclaimed effluents. One such waste problem with which the reclamation program will have to cope is the proper segregation of brine wastes.

Recharging Underground Reservoirs With Reclaimed Waters

The success of water-spreading operations, long conducted by the Los Angeles County Flood-Control District, has been demonstrated and the operation throughout the county is well recognized as an effective conservation of seasonal flood runoff (figs. 57–58).

This spreading operation, along with the importation of Colorado River water, has done much to ameliorate the ground-water shortage. The development of facilities for water reclamation from sewage, wherever possible near spreading grounds, and the return of reclaimed water through such spreading grounds to underground reservoirs would furnish an additional year-round supply of valuable water to the depleted underground basins.

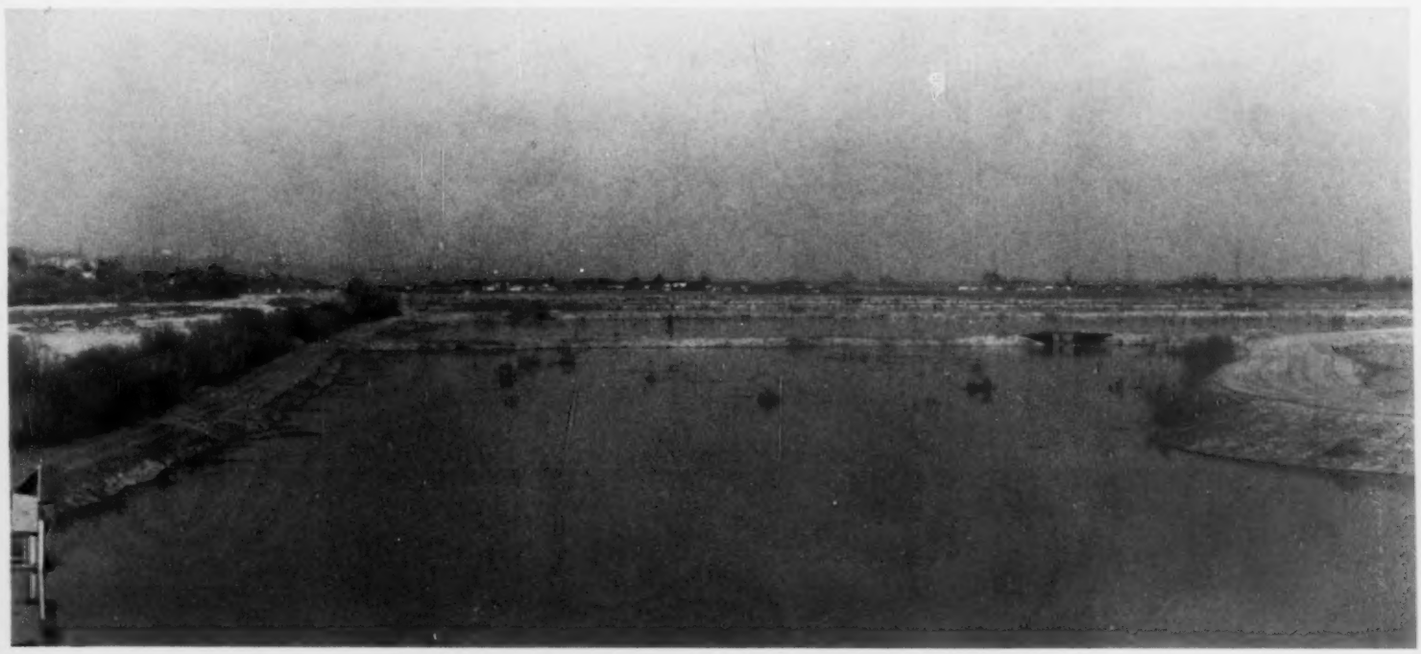

FIGURE 58.—*Rio Hondo spreading grounds (water spread for recharge).*

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